ELECTRICAL ENGINEERING

FEBRUARY IN TWO SECTIONS—SECTION II 1943

Vol. 62
1943

PUBLISHED MONTHLY BY THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STRONG AS SAMPSON

BUT LICKED BY A RAINDROP

Strength in line hardware is merely a matter of putting enough metal in the right place. But, then, time comes into the picture. "Enough metal" may not be there after a few years' corrosion has done its work... There is one sure way to keep all the metal you originally bought. Buy O-B malleable iron! The long-lived, galvanized coating is re-enforced by an inherent property of this metal... A characteristic of malleable iron is the formation of an almost indestructable coating of iron-oxide that sticks tightly to the base metal. Unlike certain other ferrous metals, this coating will not erode away to expose fresh surfaces underneath. One coating of rust, and the metal is then protected permanently by Nature... O-B hardware doesn't "wash away" over a period of time. Corrosion doesn't alter design; doesn't reduce vital dimensions. Years later, you still have all you originally bought... That's one reason why O-B uses malleable iron for line hardware. That's why you should cash in on O-B's experience in both material and design.

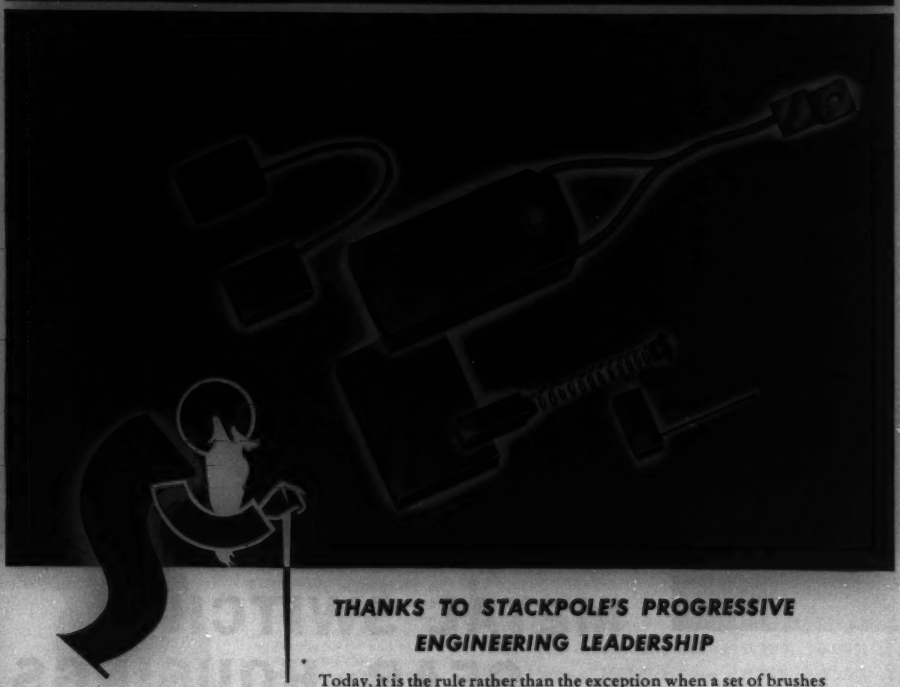
Ohio Brass

2348-H

MANSFIELD, OHIO

Canadian Ohio Brass Co., Ltd., Niagara Falls, Ontario

BETTER BRUSHES *for Today's Jobs*



THANKS TO STACKPOLE'S PROGRESSIVE ENGINEERING LEADERSHIP

Today, it is the rule rather than the exception when a set of brushes lasts the entire life of a fractional horsepower motor or generator.

Even more important—if less spectacular, however—are the Stackpole-engineered brush improvements for heavy-duty equipment. Progressing steadily over more than a third of a century, these have played an increasingly important part in paving the way for greater capacity equipment in less weight, higher speed operation, better insulation, and generally improved performance under more exacting conditions.

To the careful buyer, the consistency of these Stackpole developments is significant. It means that brush problems don't stay answered. Last year's answer may be obsolete today. And, certainly, it means that it pays to check brush requirements at frequent intervals with the latest that Stackpole engineering may have to offer.

STACKPOLE CARBON COMPANY, ST. MARYS, PENNA.

Other Stackpole Molded Products

Molded Rare Metal Contacts • Carbon, Graphite, and Composition Contacts • Anodes • Electrodes • Brazing Blocks • Bearings • Pipe • Welding Rods, Electrodes and Plates • Packing, Piston, and Seal Rings • Rheostat Plates and Discs • Brake Lining, etc.

Stackpole Electronic Components

Fixed and Variable Resistors • Iron Cores • Switches

Stackpole brushes are made in carbon, carbon graphite, electro graphite, silver graphite, copper graphite, and in metal composition types for all rotating machines. Sold only to manufacturers of original equipment.

STACKPOLE

EVERYTHING IN CARBON BUT DIAMONDS

ELECTRICAL ENGINEERING. Published monthly by the American Institute of Electrical Engineers; publication office 20th & Northampton Streets, Easton, Pa. Editorial and advertising offices: 33 West 39th Street, New York, N. Y. Subscription $12 per year, plus extra postage charge to all countries to which the second-class postage rate does not apply; single copy $1.50. Entered as second-class matter at the Post Office, Easton, Pa., under the Act of Congress of March 3, 1879. Accepted for mailing at special postage rates provided for in Section 538, P.L. & R. Act of February 28, 1925.

February 1943. Vol. 62, No. 2 Number of copies this issue 24,650

KIRK & BLUM

METAL SWITCH GEAR HOUSINGS

The illustration shown is part of a large order of cubicles for switch gear housings for a large power development project in the southern territory.

This is but one of many special items of sheet metal, steel plate and light structural products, such as, Busway Enclosures, Switch Board Panels, Control Desks, and Control Panels, fabricated by Kirk & Blum, under recent large contract orders from industries in the electrical field.

For more than a third of a century, we have been fabricating special sheet metal products from customers' blue prints and individual specifications.

Consult Kirk & Blum Engineers. Their specialized experience gives them a decided advantage in analyzing your problems, to make recommendations of how we can fabricate your products with utmost speed and economy.

Send us your blue prints for prompt quotations.

Send for any of the following booklets:

"Data on KIRK & BLUM Production Facilities"
"Dust Collecting Systems in Metal Industries"
"Fan Systems for Various Industries"
"Blower Systems for Woodworking Plants"
"Industrial Ovens"
"Cooling Systems for the Glass Industry"

ACCURATE SHEET STEEL FABRICATION — CAPACITY 1/8 INCH and LIGHTER

THE KIRK & BLUM MANUFACTURING CO.
AN ORGANIZATION OF ENGINEERS AND CRAFTSMEN
2855 SPRING GROVE AVE. CINCINNATI, OHIO

Insulation Stability at High Temperature with Metallized Paper Tapes

● *Oven maintained at 100° C. for long time aging tests on power cables, — following the practice developed by one of the major utilities. The samples with ends sealed are placed in the oven. Periodic power factor measurements are checked against initial values. A cable with poor aging characteristics will show a marked increase in power factor under these severe conditions.*

Today's heavy loads on power cables develop temperatures that will hasten deterioration of the insulation unless the proper safeguards are incorporated.

Studies made in the Okonite-Callender Research Laboratories have shown that one of the big factors in the deterioration of oil-impregnated paper-insulated cables is the effect of the metal in contact with the oil. Copper especially has a very pronounced reaction.

Careful analysis proved that these reaction products were concentrated in the first tapes directly over the conductor and also adjacent to the sheath. Our research engineers searched for and found a method of stopping these harmful products (formed by the reaction between copper and oil) from entering the dielectric.

By applying metallized paper tapes under and over the insulation, an efficient absorption medium is provided that also functions as a barrier for holding the harmful products out of the insulation itself.

The results of radial power factor tests (previously published — Bulletin OK-2022) clearly demonstrate these advantages. They have also been confirmed after long time aging tests of the cable itself as indicated below.

	Length A	Length B
Initial Power Factor	0.31%	0.29%
After 1 year at room temperature	0.29%	0.30%
After 1 year at 100° C. in oven	0.34%	0.33%

Tests records show this remarkable stability as checked on two 20-foot lengths of 12 K.V. three-conductor Okonite-Callender cable with metallized paper tape barriers. Practically no change in power factor takes place.

When you are considering paper-insulated cable, it will pay you to have our engineers show you all the facts on this and the many other developments made

Through OKONITE-CALLENDER RESEARCH

THE OKONITE-CALLENDER CABLE CO., INC.

An Affiliate of The Okonite Company

Executive Offices: Passaic, N. J. • Offices in principal cities

OKONITE CALLENDER

3300

Salvage Your Scrap — Buy U. S. War Bonds

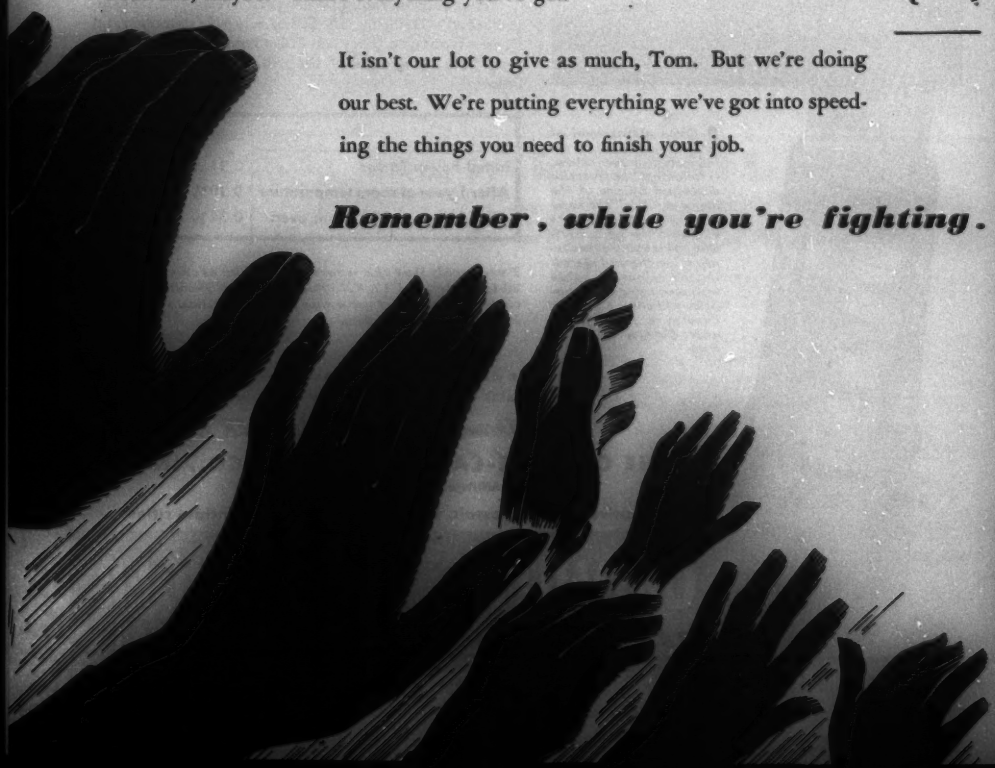
See You Soon, Tom!

We don't know where you're going, Tom. We don't know when you'll be back. But it's got to be soon!

We know what you're giving up. Your swell job at the plant, your picnics with Jane, the workshop in your basement, your quiet dreams of the future. Your life, maybe. That's everything you've got.

It isn't our lot to give as much, Tom. But we're doing our best. We're putting everything we've got into speeding the things you need to finish your job.

Remember, while you're fighting.



. . we're fighting, too!

Thinking about Tom—the hundreds of Toms who waved goodbye at American Lava and went to war—makes our seconds precious. So we work around the clock, create startling improvements in AlSiMag steatite ceramic insulation, devote ourselves exclusively to winning the War. In the process, we continually find ourselves saying "no" to the urgent needs of old friends who have bought our products for four decades or more. We regret that. Today, we answer the greater need.

ARMY ( ) NAVY

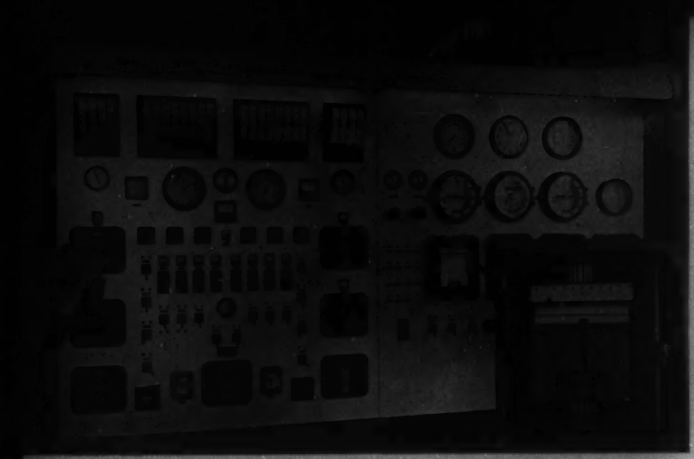
The ALCO plant was on the first list of 43 awards for excellence in quality and quantity of war production.

AlSiMag

TRADE MARK REGISTERED U. S. PATENT OFFICE

AMERICAN LAVA CORPORATION

CHATTANOOGA, TENNESSEE



A central station arranged its L&N boiler-control equipment as shown here. Included are Metermax Combustion Control, Micromax Round-chart Recorders for superheated steam, steam purity and CO_2, and a Micromax Strip-chart Recorder for air, gas and water temperatures.

Micromax Recorder with tear-off device which makes removal of day's record as simple as removal of a round chart.

STRETCH YOUR MANPOWER
With Instruments & Controls by L&N

Supplied one at a time, or in completely-assembled panels, L&N's dependable, fully-automatic instruments and controllers are helping many a power plant which must stretch its remaining manpower. Typical groups of equipment are shown here.

Micromax Flow Recorder. For accurate determination of steam and water flow. The meter-body is the revolutionary, highly precise Centrimax (centrifugal-force) machine. Integrating and recording are separate, independent functions; neither affects the other. Integration is on the Recorder's counter; rate-of-flow is shown on record in typically thorough, visible, finely-detailed Micromax fashion. Recorder may be Strip-chart or Round-chart. For further information, write us or see Catalog N-28-160, 1942 edition.

Micromax Temperature Recorders. Multipoint instruments supplying multicolor (or single-color) records of temperatures of steam, gas, air, water, from any points at which thermocouples or Thermohms (resistance - thermometer bulbs) can be located. Records are extremely legible. Instruments may be equipped for automatic control of superheat. For further information, write us.

Micromax CO_2 Recorder. The simple, accurate, sensitive equipment which requires hardly more attention than does a pyrometer. Can be either a guide to manual adjustment of combustion, or can automatically operate fuel-air ratio setting of Metermax Combustion Control. For further information, write us, or see Catalog N-91-163, 1941 ed.

Metermax Combustion Control. For helping boiler furnaces meet any load conditions, without sacrifice of efficiency. Combines the sensitivity of electric control with the simplicity of pneumatic, to form equipment of outstanding dependability for medium and large plants. For further information, write us, or see Catalog N-01-163, 1939 ed.

Boiler-control panel in the powdered-coal power plant of a cement mill. Recorders, left to right, are Micromax for feedwater-flow; Micromax multipoint multicolor for temperatures of gas, air, feedwater and superheated steam; Micromax multipoint multicolor for temperatures of condensate and makeup; and, below, Micromax CO_2 Recorder. Shown also is complete Metermax Combustion Control. Complete assembly and wiring of this panel was done by L&N.

Jrl Ad N-163(9)

LEEDS & NORTHRUP COMPANY, 4962 STENTON AVE., PHILA., PA.

LEEDS & NORTHRUP

MEASURING INSTRUMENTS · TELEMETERS · AUTOMATIC CONTROLS · HEAT-TREATING FURNACES

NEW "Rub-r-Less" WIRE

NO RUBBER, NO SYNTHETIC, NO TIN

1 Transversely crumpled, moisture-resistant Kraft 2 Cellulose-acetate butyrate (Kodapak No. 2) insulation 3 No tin or alloy coated copper 4 "Dilec" cotton serving 5 Moisture-resistant, flame-retardant finish

Made in all sizes, 14 to 1,000,000 CM, and in standard colors—black, white, red, blue, green and yellow.

Lead covered "Rub-r-Less" Wire Type "ELL" with standard wall thickness of lead, also CAA specification, lead covered with 2 "Dilec" servings over the lead for underground work.

Approved by the Underwriters' Laboratories Inc. for use as a substitute for rubber insulated wire under conditions stated in Interim Amend. Nos. 44 and 69 covering Section 3005 of the N. E. Code.

Conforms to Department of Commerce CAA-612 Specification also Section 34 War Department Office of Chief Engineers Specification for Theater of Operations and Mobilization Construction. "Rub-r-Less" Wire is also included in suggested specifications to architects issued by Federal Works Agency, Public Building Administration.

Distributed through National Electric distributors throughout the United States.

National Electric
PRODUCTS CORPORATION
Pittsburgh Pennsylvania

Amazing NEW GLASS

mail coupon today for

A QUICK CHECK LIST FOR ENGINEERS!

ENGINEERING PROPERTIES OF PYREX MULTIFORM GLASS VS. OTHER INSULATING MATERIALS

GLASS CODE		790	7761	707	774	Steatite*	Electrical Porcelains*
GLASS TYPE		Multiform Glass	Multiform Glass	Multiform Glass	Conventional Glass		
ENGINEERING PROPERTIES	UNIT						
DENSITY	—	2.15	—	2.10	2.23	2.5—2.8	2.3—2.5
SOFTENING TEMPERATURE	°C	—	—	—	820	1250—1400	1500—1600
MAX. OPERATING TEMPERATURE	°C	900	500	425	500	60—90	90—50
LINEAR EXPANSION (0-300°C)	per °C X 10^{-7}	8.5	—	32	32	0—0.1	0—2.0
WATER ABSORPTION—24 HRS.	%	<.01	<.01	<.01	NONE		
MODULUS OF RUPTURE —ANNEALED GLASS	LBS./IN.^{2} X 10^3	5	7	7	10	—	6—12
MODULUS OF RUPTURE —SPECIAL PROCESS	LBS./IN.^{2} X 10^3	—	—	12	18	17—24	
VOLUME RESISTIVITY		—	—	—	14.7	14	12—14
LOG R AT 20°C	OHMS PER	9.3	—	—	8.1	9—14	7—10
LOG R AT 250°C	CM. CUBE	7.8	—	—	6.7	8—13	6—8
LOG R AT 350°C	—	4.0	4.0	4.0	4.65	5.5—7.5	5.0—7.5
S. I. C.—20°C—1 MEG.	%	0.18	0.11	0.10	0.42	0.03—0.30	0.70—1.2
P. F. —20°C—1 MEG.	%	0.72	0.44	0.40	1.95	0.15—1.54	3.5—9.0
L. F. —20°C—1 MEG.	%						
DIELECTRIC STRENGTH	VOLTS/MIL	>500	>500	>500	HIGH	200—300	200—290

*Data from Rieterink, M. D., *Review of Scientific Instruments*, vol. 12, no. 11, 627-634 (1941).

INSULATORS . . .

free sample and data!

ALMOST NO LIMITS ON SIZE OR SHAPE

IF you need insulators, here's what you've been waiting for! Corning Glass Research announces new types of electrical insulators—Pyrex brand Multiform Glassware. Its general characteristics include low loss factor, high dielectric strength, negligible water absorption, adequate mechanical strength. For example, Multiform glass Number 790 (see chart on opposite page) meets requirements of U. S. Navy Standard RE-13A-317F. And all Multiform glasses comply with the proposed A.S.A. American War Standard on Radio Insulation Materials of Low Dielectric Constant.

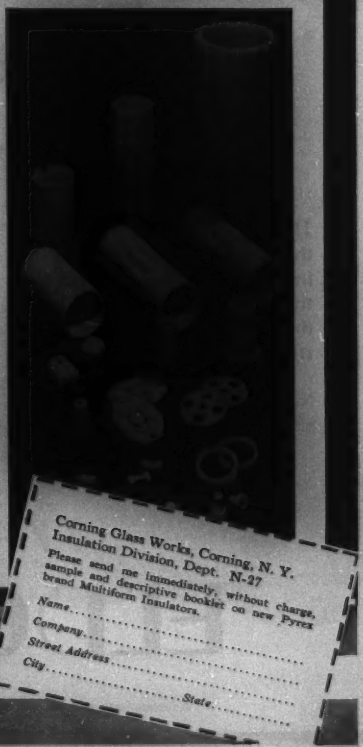
The characteristics of these glasses plus Corning's new fabrication methods make possible an extremely wide range of shapes and sizes. General dimensional tolerances are: large or heavy pieces, intricate shapes, hollow cylindrical sections—±2.0% or 0.010″; flat plates, solid rods, discs, beads, bushings—±1.0% or 0.005″, except thickness which should be ±4% or 0.005″.

Best of all, glass-making materials are still fairly plentiful. Pyrex brand Multiform Insulators are available NOW! Mail the coupon today for a free sample and a descriptive booklet just off the press.

* * *

Pyrex brand Multiform Glassware is particularly adapted to manufacture in such shapes as solid cylinders, plates with one or many holes, large heavy-walled articles, coil forms, hollow cylindrical beads, and many other articles in a wide variety of shapes. In size and weight, these insulators run the gamut from small beads, several thousand to the pound, to large pieces with maximum dimensions up to 15″, weighing 25 pounds each or more.

MAIL COUPON TODAY!



Corning Glass Works, Corning, N. Y.
Insulation Division, Dept. N-27

Please send me immediately, without charge, sample and descriptive booklet on new Pyrex brand Multiform Insulators.

Name.....

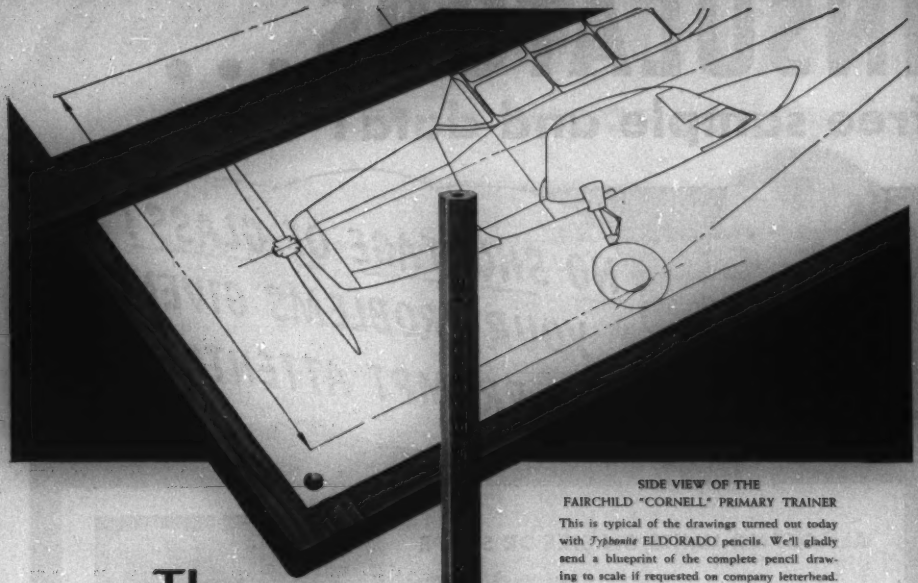
Company.....

Street Address.....

City.....State.....

Pyrex Insulators
BRAND

"PYREX" is a registered trade-mark and indicates manufacture by Corning Glass Works



SIDE VIEW OF THE
FAIRCHILD "CORNELL" PRIMARY TRAINER

This is typical of the drawings turned out today with *Typhonite* ELDORADO pencils. We'll gladly send a blueprint of the complete pencil drawing to scale if requested on company letterhead.

The Mighty Pencil

The man behind the ELDORADO is a threat to the Axis. His lead is proving as deadly as the kind used by the man behind the gun. His job is that of creating the blueprints of destruction to destroy said Axis.

• • •

Never underestimate the value of *Typhonite* ELDORADO pencils in America's drafting rooms. They're doing magnificent work! Drawings made with *Typhonite* ELDORADO leads insure clean, easy-to-read blueprints... *in less time.* There's no time out for inking in... the density and accuracy of ELDORADO'S leads guarantee blueprinted whites sharp—readable.

TYPHONITE
ELDORADO

PENCIL SALES DEPARTMENT 42-J2 JOSEPH DIXON CRUCIBLE COMPANY, JERSEY CITY, N. J.

EVEN war can bring out much that is good.

The gauging of thin mica sheets threatened to be a production bottleneck. Fingers, highly trained by the Braille system, were called upon to replace mechanical gauges and slower vision. The fingers responded.

Today a group of blind employees at SOLAR are gauging mica quicker and more accurately than ever achieved before. They and their "seeing-eye" dogs bring unusual talents to the production front.

"HANDS THAT SEE"

SOLAR is proud to be a pioneer in drawing upon the untapped reservoir of such able employees. SOLAR "Quality Above All" is well protected by these "hands that see."

Solar

SOLAR

SOLAR MANUFACTURING CORP., BAYONNE, N. J.
Makers of Capacitors (Mica, Paper and Electrolytic)

CAPACITORS

This is the way to win a battle in the desert

Libya and North Africa made it clearer than ever: THIS IS A WAR OF SUPPLY.

In 1918, an American soldier could be equipped and maintained on 5 tons of supplies each year.

But today, for every soldier sent abroad, *10½ tons* of shipping space must be provided for *equipment alone*. And it takes an additional *18 tons of shipping to supply a single soldier for a year!*

Supply is a matter of *ships*.

And ships need electricity.

Vast quantities of electric power, for a thousand vital tasks that must be done to take a convoy safely across the seas...

Electricity to steer the vessels and operate the radios and signal lights.

Electricity to detect the approach of enemy subs and planes, to sound the alarm, to organize the defense.

Electricity to power great cargo winches, and delicate navigating instruments.

Electricity to make magnetic mines harmless, to provide invisible "black light" for reading charts at night. Electricity to keep food fresh, to cook it, to ventilate the ships, to provide comfort for the crews.

Electricity in every freighter, every tanker, every Navy escort vessel—to help win the war of supply!

We of Westinghouse take tremendous pride in building so much of the electrical equipment, so many of the great turbines and gears and electric drives, for the ships of America's Navy and Merchant Marine.

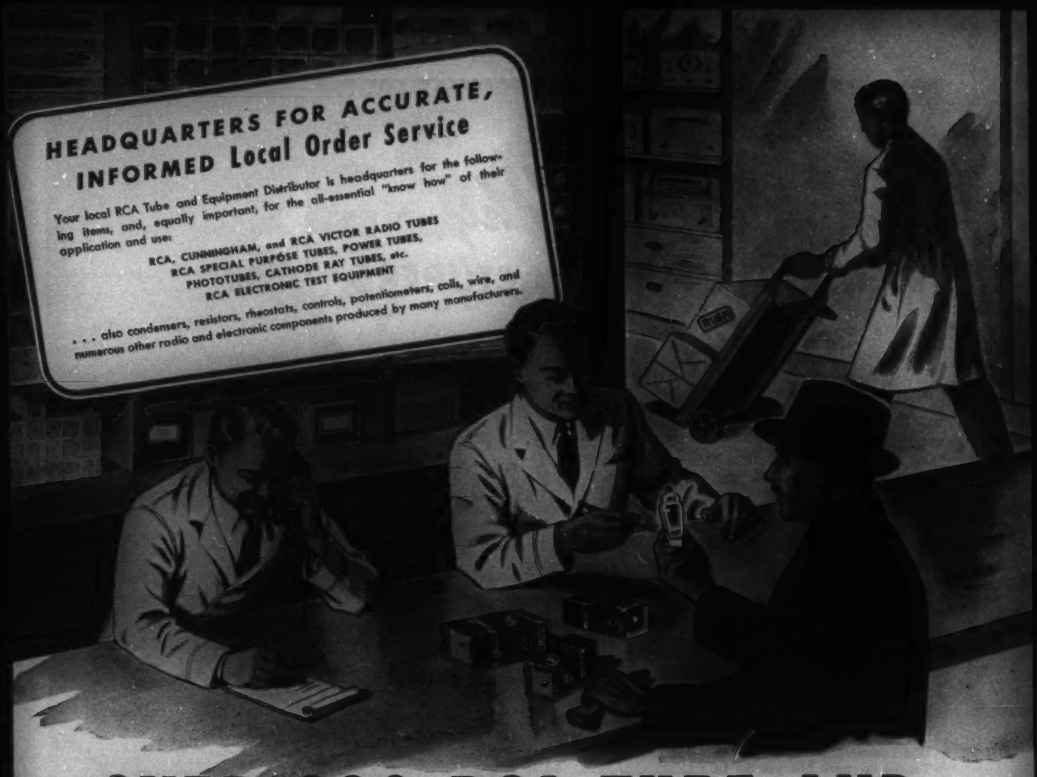
Into every piece of that equipment go all our "know-how," all our skill, all our determination to *do our share* in this war—and if possible, a little more.

Westinghouse Electric & Manufacturing Company, Pittsburgh, Pennsylvania.

Tune in the Westinghouse Program starring John Charles Thomas — NBC Network, Sunday, 2:30 P. M., Eastern War Time.

Westinghouse

PLANTS IN 25 CITIES — OFFICES EVERYWHERE


HEADQUARTERS FOR ACCURATE, INFORMED Local Order Service
Your local RCA Tube and Equipment Distributor is headquarters for the following items, and, equally important, for the all-essential "know how" of their application and use:
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RCA SPECIAL PURPOSE TUBES, POWER TUBES,
PHOTOTUBES, CATHODE RAY TUBES, etc.
RCA ELECTRONIC TEST EQUIPMENT
. . . also condensers, resistors, rheostats, controls, potentiometers, coils, wire, and numerous other radio and electronic components produced by many manufacturers.

OVER 300 RCA TUBE AND EQUIPMENT DISTRIBUTORS

. . . TO SERVE YOU LOCALLY!

WHETHER your need is for one electronic item or a dozen, your RCA Tube and Equipment Distributor is geared to help you select it and get it as rapidly as possible! The fact that there are over 300 of these distributors throughout the nation means that there is one close by—ready to deliver personalized, 'round-the-corner service.

RCA Tube and Equipment Distributors not only afford a convenient, 'round-the-corner source of supply, but back their merchandise with a technical knowledge that has proved invaluable.

If you do not already know the name of your nearest RCA Distributor, write or wire us today.

Put his services to work in solving your electronic equipment buying problems. Take advantage of the large stocks he normally maintains. Let him serve as your specialized "expediter" on orders that must be deferred. Ask him for the technical suggestions he is so well qualified to give!

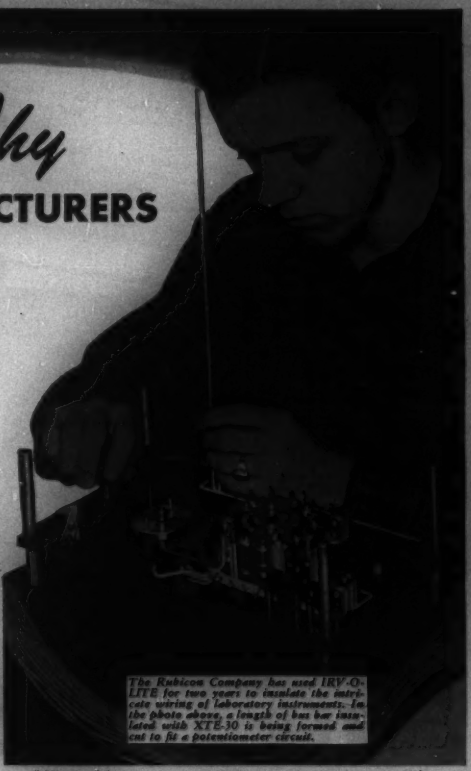
RCA MANUFACTURING CO., INC., Camden, N. J.

AN ADVERTISEMENT OF THE RCA TUBE AND EQUIPMENT DIVISION IN THE INTEREST OF GREATER SERVICE AND EFFICIENCY IN PRIORITY-COVERED WAR MATERIALS BUYING

Here's Why

ELECTRICAL MANUFACTURERS *buy*

IRV-O-LITE XTE-30



The Rubicon Company has used IRV-O-LITE for two years to insulate the intricate wiring of laboratory instruments. In the photo above, a length of bus bar insulated with XTE-30 is being formed and cut to fit a potentiometer circuit.

Whether used as wiring or lug insulation or as conduit, this extruded plastic tubing will do a good job even under difficult conditions. It has been employed on tiny, fractional horsepower motors and on giant aircraft; in the construction of sensitive laboratory equipment and in rough-riding Army tanks.

IRV-O-LITE XTE-30 is suitable for such diverse installations because random samples consistently live up to these standards:

Dry Dielectric Strength	750 VPM
Wet Dielectric Strength	350 VPM
Tensile Strength Lbs. per Sq. In.	2,150
Elongation	250%
Resistance to Brittleness. Standard wall XTE tubing does not shatter when slowly pinched with pliers at	—40 deg. F.
Life at 105° C.	400 hrs.
Wemco Oil Immersion 48 hrs. at 100° C. Intact, can be flexed	
Resistance to 50% Sulphuric Acid at 72° F.	Unaffected
Resistance to 30% Sodium Hydroxide at 72° F.	Unaffected
Resistance to Mineral Solvents	Excellent
Resistance to Coal Tar Solvents	Good

In addition to being unusually flexible and elastic over a wide range of temperatures, XTE-30 tubing is also highly resistant to tearing and abrasion.

IRV-O-LITE XTE-30 is produced in sizes ranging from A.S.T.M. No. 24 to 1½" I.D. and in six opaque colors, black, green, white, yellow, red and blue, to simplify identification of circuits. Standard lengths are 36-inch pieces and 25-ft. coils. Continuous length coils and cut pieces from ¼" to 12" can also be furnished.

NEW! Most recent addition to the Irvington Fibronized tubing line, XTE-130 was developed to withstand unusually high temperatures. Samples of No. 9 opaque have yielded an oven life of 500 hrs. at 125° C. (257° F.), 1000 hrs. at 105° C. (221° F.).

IRV-O-LITE XTE-130 offers a dielectric strength of 1000 VPM both wet and dry, tensile strength of 4000 lbs. per sq. in. Although slightly less flexible than XTE-30 at room temperature, this tubing resembles it in other respects. XTE-130 is obtainable in black, green, white, yellow, red, blue and clear, in A.S.T.M. sizes No. 20 to 1½" I.D. and same lengths given above.

For additional information or for testing samples write Dept. 36.

Over 25,000,000 feet of IRV-O-LITE now serving industry

Irvington

STANDARD OF THE WORLD — IRVINGTON INSULATION — TRADE MARK REG. U.S. PAT. OFF.

VARNISH & INSULATOR CO.

Representatives in 20 Principal Cities

IRVINGTON, NEW JERSEY, U. S. A. • PLANTS AT: IRVINGTON, NEW JERSEY & HAMILTON, ONTARIO, CANADA

VARNISHED CAMBRIC • RUBBER POWER CABLES • BUILDING WIRE • RADIO WIRES • SIGNAL CABLE • FLEXIBLE CORDS • LEAD-ENCASED AND PARKWAY CABLES • ARMORED CABLE • CRESFLEX NON-METALLIC SHEATHED CABLE • SERVICE ENTRANCE CABLE • MAGNET WIRE • BARE WIRE

CRESCENT

is Helping To Win This War

ON THE HOME FRONT, TOO

In thousands of factories and shops whose production is devoted 100% to the war effort, power is supplied through CRESCENT *Wire and Cable.*

CRESCENT INSULATED WIRE & CABLE CO.

CRESCENT
WIRE and CABLE
Factory: TRENTON, N. J.—*Stocks in Principal Cities*

CRESCENT ENDURITE SUPER-AGING INSULATION • WEATHER-PROOF WIRE

Alcoa departed from tradition when they first introduced Aluminum as a conductor material to the electrical industry. Imagineering at work, forty-odd years ago, visualized a new, high conductivity, lightweight, corrosion-resistant conductor material. Then they engineered it into reality; first all-Aluminum, then A. C. S. R.

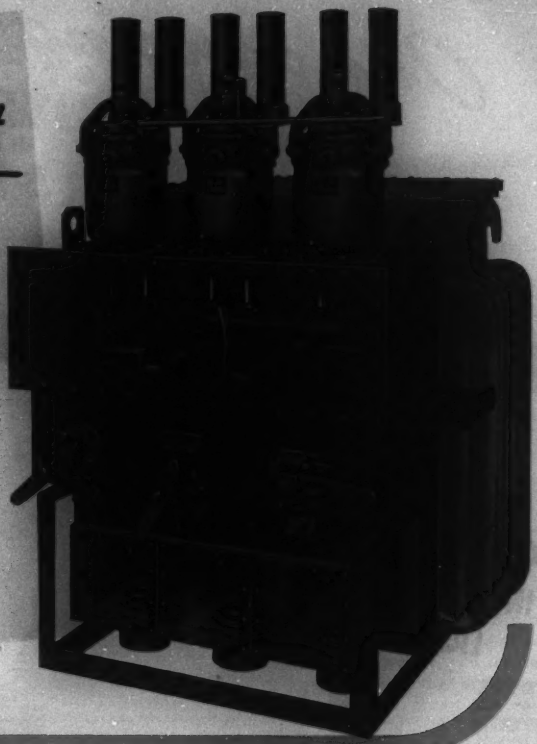
A million miles of Aluminum Cable Steel Reinforced, in service on hi-lines and rural lines all over America, long ago proved the sound thinking of those early Imagineers. Aluminum bus conductors, in the form of flat bars, tubing and channels, have also proved their worth in central stations, substations and industrial plant distribution systems.

Today, new concepts of Aluminum arise from the swift technological advances resulting from the war effort and the greatly increased Aluminum production. New joining methods, new fabricating procedures, new alloys, new commercial forms, all combine to provide new economies and to broaden post-war applications of Aluminum.

Many of these new applications will be electrical. Versatile Aluminum will become an even more important tool in the hands of the electrical engineer. We'll gladly discuss the economic aspects of Aluminum with you as they apply to your design problems. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh, Pennsylvania.

G & W *Forethought*

COMBINES THE FEED CIRCUIT SELECTOR OIL SWITCHES AND BRANCH CIRCUIT OIL FUSE CUTOUTS INTO A COMPACT METAL ENCLOSED UNIT FOR DIRECT ATTACHMENT TO THE TRANSFORMER.



TYPE "MSF" MULTIPLE SWITCH FUSE UNIT

Here is real forethought . . . planning in advance for easier installation of equipment to fit into a smaller space. Also to provide for safe, economical and trouble-free distribution system flexibility . . . Make your transformer a pre-designed unit complete with accessories.

The practical design and simple construction of G & W Type "RA" multiple circuit Oil Disconnects have proved very satisfactory. The G & W Type "FC" Oil Fuse Cutouts have become an accepted standard for metal-enclosed primary fusing . . . *Combine these G & W devices with your transformers and let factory assembly take the place of field work.*

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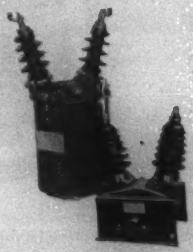
POTHEADS . . . BOXES . . . OIL FUSE CUTOUTS . . . OIL SWITCHES AND MULTIPLE CIRCUIT OIL DISCONNECTS

Announcing

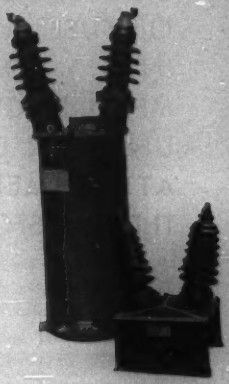
NEW OUTDOOR POTENTIAL TRANSFORMERS

THAT SAVE VITAL MATERIALS

NOTE THESE REDUCTIONS IN SIZE, WEIGHT, AND LIQUID VOLUME



24,000/120 Volts



34,500/115 Volts

	Type E-116	Type E-236
Height—inches	42	34¼
Width of Base—inches	15¼	18
Net Weight—pounds	350	320
Liquid Volume—gallons	9	5

Type E-116	Type E-236
71	36½
19	19
850	350
45	6

HERE ARE THE SAVINGS the Type E-236 transformers make possible for you—in addition to saving vital materials in manufacture.

SAVE SPACE

Their light weight and small size enable you to mount them in the steel structure and thereby save valuable ground space.

SIMPLIFY CONNECTIONS

Mounting in the structure simplifies primary (high-voltage) connections.

SAVE FOUNDATION EXPENSE

Mounting in the structure also eliminates the need for constructing a separate foundation.

REDUCE MAINTENANCE

The insulating liquid need not be tested or inspected, because it is hermetically sealed in—there are no gaskets on these tranaformers.

CHARACTERISTICS

All improvements have been accomplished without any sacrifice in accuracy or insulation—the two most important characteristics of any instrument transformer.

ACCURACY—These transformers meet the highest accuracy classification, ¼W, ¼X, ¼Y, ¼Z, and they are suitable for both metering and relaying.

INSULATION—Ample insulation is provided to meet the ASA standards for impulse tests, as indicated by the following test data:

Transformer Voltage	Dielectric Tests	
	Full-wave, Kv	Low-frequency, Kv
24,000/120	150	51
34,500/115	200	70
46,000/115	250	93
69,000/115	350	140

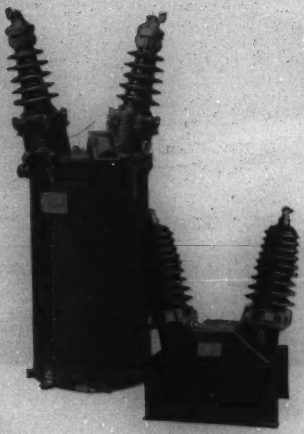
GENERAL ELECTRIC

TYPE E-236

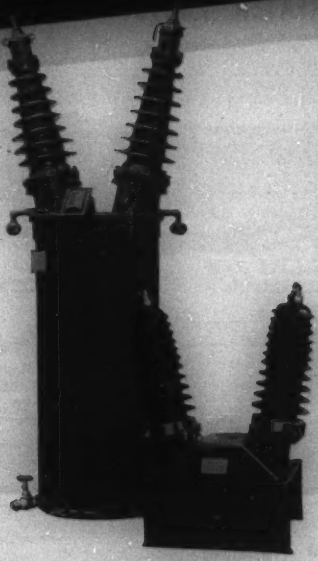
TWO-BUSHING

PYRANOL OR OIL-FILLED 24 KV TO 69 KV

They Supersede the Type E-116



46,000/115 Volts



69,000/115 Volts

Type E-116	Type E-236
81¼	45
26¼	21½
1700	550
100	9

Type E-116	Type E-236
108	55½
26¼	28½
2400	1000
125	20

Completes Our Line of Small-size Outdoor Current and Potential Transformers

BECAUSE you can get G-E outdoor current and single-bushing potential transformers of corresponding small size and light weight, you can take full advantage of the small size of these new two-bushing units. You can now mount all your transformers up in the structure, and get the full benefit of foundation savings.

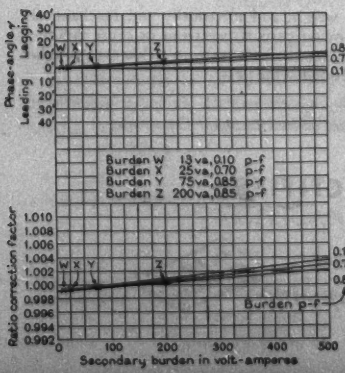
All these transformers are available filled with Pyranol* (or oil if you prefer). Because instrument transformers are such a vital link in the protection of your system, you'll want to insist on Pyranol—the G-E insulating and cooling liquid which is chemically stable. It means greater safety, too. It is noninflammable.

You can adopt G-E instrument transformers as standard for your system. General Electric makes a complete line of indoor currents and potentials, and portables as well.

For additional information about these new E-236 units, ask for Bulletin GEA-3982. Also, the specialist in the nearest G-E office will be glad to work with you in applying instrument transformers for either metering or relaying.

General Electric Company, Schenectady, N.Y.

*Reg. U.S. Pat. Off.



Ratio and phase-angle curves of the 69-kv unit—at 60 cycles, 115 secondary volts. (This is typical of the curves for all these transformers.)

The Army-Navy "E", for Excellence in the manufacture of war equipment, now flies over six G-E plants employing 100,000 men and women.

Special Assembly Method — *showing single metal washer which facilitates protective coating against corrosion*

Standard Assembly Method—*showing conventional petal-shaped brass contact washer*

Now I. T. & T. Selenium Rectifiers—in addition to the standard assembly—can be supplied with a special assembly, coated for protection against the corrosive action of salt spray, moisture and humidity.

This means that I. T. & T. Selenium Rectifiers, noted for trouble-free conversion of A.C. to D.C., can now be used under the extreme conditions of marine and other high-humidity service.

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FEBRUARY

1943

The Cover: An M-4 tank in action. Electricity performs essential control and communication functions in these mighty "battleships of the land." Official OWI Photo by Palmer

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HIGH LIGHTS . . .

Equivalent Circuit. A practical equivalent circuit for a five-winding transformer is presented, together with a development of the necessary formulas. Examples show how the various equivalent-circuit parameters are evaluated, and factors affecting the voltage regulation of the transformer are brought out with the aid of an example in which two sources of supply are present (*Transactions pages 66–70*).

Emergency Loading of Transformers. By locating portable capacitor units at strategic points on a power system, permissible loading of closed-delta transformer banks may approach the safe thermal limit and still be operated in open delta in emergency. The mobility, light weight, and simplicity of connection permit rapid installation of the portable capacitor units (*Transactions pages 83–6*).

Letters to the Editor. Among subjects discussed in the "Letters to the Editor" columns of this issue are regulation and load division in a three-phase, four-wire network (*pages 84–5*); terminal corrections for temperature tests on short conductors (*pages 83–4*); capacitance and dissipation-factor correction (*pages 85–6*); and static electricity in gasoline fires (*page 83*).

Electromechanical Calculator. An electromechanical calculator, designed for the rapid solution of directional-antenna patterns, draws the field-intensity curve automatically to any desired scale on a sheet of polar co-ordinate paper and indicates the rms value for drawing a circle of the equivalent nondirectional pattern (*Transactions pages 78–83*).

Switching Overvoltage Hazard. Suitable resistors, interposed across the interrupting elements during the opening stroke of a high-voltage oil circuit breaker, may either eliminate the switching overvoltages by preventing restriking, or reduce them in magnitude in the event of restriking so that the transmission system is relieved of their hazard (*Transactions pages 98–106*).

Linear Conductors of Structural Shape. Many busses for heavy-current duty now are being constructed of linear conductors of structural shape because of their many mechanical and electrical advantages. Formulas are derived in a paper in this issue for the inductance of busses composed of such conductors (*Transactions pages 53–8*).

Stability Study. An analysis to determine basic performance data of series-capacitor-compensated long-distance transmission lines under steady-state and transient conditions partly answers the question of where reactance compensation is applicable, and also permits certain general conclusions to be drawn (*Transactions pages 58–65*).

Equivalent Ambient Temperatures. Monthly equivalent ambient temperatures, obtained through calculations based on weather-bureau records, can be used in combination with load curves for determining the permissible safe overload for a transformer in a given locality (*Transactions pages 87–93*).

Wood-Pole 230-Kv Line. Problems encountered in the construction of a 230-kv transmission line with wood-pole structures include the stresses involved, foundation requirements, and dimensions of structural members necessary to maintain separations between conductors and ground clearances (*Transactions pages 94–7*).

Distribution-Factor Error. A method is presented of correcting a common error often made in the use of the distribution factor of electric machines when a winding consists of a fractional number of coils in series. The method also assists in determining the best distribution of such a winding (*pages 68–72*).

British Engineering Corps. The recent formation of the Royal Electrical and Mechanical Engineers is expected to bring electrical and mechanical engineering maintenance in the British Army under single control. The organization and function of this new unit are described in this issue (*pages 80–1*).

Paired-Phase Bus Bars. A new paired-phase method of arranging bus bars is said to have excellent temperature rise, voltage drop, energy loss, and structural characteristics for polyphase currents in the range of 1,000 amperes and above at 600 volts and less (*Transactions pages 71–7*).

Wartime England. How industries, utilities, and civilians in England have rallied to meet the exigencies of air attack is told in this article, which points out how various phases of life in England have been keyed to war conditions (*pages 55–60*).

Pasteurization. Some up-to-date information on electric pasteurization is presented in this article along with a brief history of the process. Temperature control, vital factor in pasteurizing, is discussed in some detail (*pages 60–3*).

Airport Lighting. Wartime and black-out regulations have made it necessary to reduce airport lighting. Methods for operating airport lights in accordance with these regulations are suggested in this article (*pages 64–7*).

Conservation. United States Army agencies are easing wartime production problems by using alternate materials in a variety of war supplies and implements (*pages 53–4*).

Coming Soon. Among the special articles and technical papers currently in preparation for early publication in *Electrical Engineering* are: a discussion of recent developments in organic plastics for electrical insulation by Thomas Hazen; an article on research in the war effort by Vannevar Bush (F '24); addresses delivered at the presentation of the Edison, John Fritz, and Hoover medals during the 1943 AIEE winter national technical meeting; analysis of a method for determining allowable overloads for transformers, which takes into consideration individual transformer characteristics, by L. W. Clark (M '42); a study of maximum continuous current-carrying capacity of copper conductors in overhead lines, as governed by certain operating limits of temperature and time, by A. H. Kidder (M '39) and C. B. Woodward; a description of a multiorifice interrupter for high-voltage oil circuit breakers by L. R. Ludwig (M '41) and W. M. Leeds (M '38); a discussion of the effect of radio frequencies of a power system on radio-receiving systems by C. V. Aggers (A '39), W. E. Pakala (A '38), and W. A. Stickel; an investigation of the use of synchronous motors with controlled excitation for suddenly applied loads by W. K. Boice (A '39), B. H. Caldwell (A '37), and M. N. Halberg (A '29); a discussion of kilowatts, kilovars, and system investments by J. W. Butler (M '38); a description of a method of calculating transmission losses within power systems by E. E. George (F '36); a study of preventive maintenance applying to traction motors and generators by J. W. Teker (A '31); a report of laboratory test results on permissible pulling loads, to which solid-type impregnated-paper lead-sheath power cable might be subjected, by A. P. S. Bellis (A '26), and an analysis of the effect of current-transformer residual magnetism on balanced-current or differential relays by H. T. Seeley (A '27).

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Wartime Material Conservation and Production Problems

W. H. HARRISON
FELLOW AIEE

An AIEE past president, now brigadier general in the United States Army, tells how certain branches of the Army, sacrificing critical materials needed for their own supplies, are effecting conservation and easing production problems through the use of substitutes. Pointing out that in the fields of conservation and substitution engineers can be of greatest value in expediting the war, he urges engineering societies to co-operate in this work.

I HAVE had the good fortune to see war production develop from the planning and speculation stage to the point where, in so far as the Services of Supply of the United States Army are concerned, current monthly production is reasonably well up to expectation, though still short of needs. Yet it is far beyond anything the most imaginative of men could have anticipated, and far beyond anything attained by the United States or any other nation through any period of its existence.

Born of 30 odd years' experience in a business wholly dependent upon forward-looking planning—advanced and sound use of pure science and applied engineering—I can say without reservation that American industry and American government, teamed up as they have been ever since war production started, have done and are doing the impossible. In making this observation, I am not unmindful of things done that should not have been done, and of things not done that clearly should have been done.

By way of explanation, I cite the history of one of the departments of the Services of Supply as contrasted with the history of three outstanding American manufacturers. During its period of growth the United States Steel Corporation (1902 to the present) has increased 3 fold; the General Motors Corporation (1918 to the present), 8 fold; the General Electric Company (1899 to the present), 30 fold; and the Ordnance Department of the United States Army (1940 to the present), 700 fold.

The reason for success in this astronomical increase is to be found in the years of sound, imaginative planning by the procurement agencies of the different services, and great credit is due to those who had the vision.

In its evolution a program of this magnitude passes through three principal phases, and at any given time the emphasis is on one of the three: in historical order, first, creation of the facilities and placement of orders; second, flow of material; and third, men and women organized and trained to do the work.

Of course, underlying and running through the entire program every day of its existence, there is broad planning and detailed co-ordination and integration, there is continued and intensive research and engineering. And there is the most exacting demand of war, second only to time itself, that is change which, incidentally, by violent contrast is the most destructive force to mass production.

The influence of change not only is felt in revisions of design and specifications to bring maximum fire power to bear on the enemy, but also, and equally important, it is felt in basic revisions of the type of combat units themselves, which is dependent in turn on the particular type warfare which must be carried on. A foot soldier in the jungles of the Pacific Southwest certainly requires different type support than one on the sands of the Mediterranean.

PRODUCTION PROBLEMS

Considering production requirements for a complement of foot soldiers as a unit of one, a motorized complement is 2, and an armored-tank complement is 5.1. From this it can be seen readily that any realignment in type of combat forces has an immediate and substantial influence on production requirements. I make reference to this to indicate there never should be and probably never will be any period of war manufacture without change, change in type and change in quantity.

By and large, the first stage of the program, creation of facilities and placing of orders, is in hand. This is no longer the limiting factor in output. The present limiting factor is flow of materials, not so much over-all flow, as a balanced flow of particular sizes, shapes, and metallurgical content. For example, in normal times alloy steels using nickel, chromium, vanadium, molybdenum, manganese, and silicon amounted to about 7 per cent of total steel requirements in the United States. Today that percentage is about 20.

Perhaps ingots of steel, copper, lead, and aluminum

Based upon a talk given before a joint meeting of the AIEE Washington, D. C., Section, with the local sections of the American Society of Civil Engineers and the American Society of Mechanical Engineers, December 9, 1942, at Washington, D. C.

W. H. Harrison, vice-president on leave from the American Telephone and Telegraph Company, New York, N. Y., is a brigadier general in the United States Army, serving as director of procurement, Headquarters Services of Supply.

may be within striking distance of minimum needs, but specified bars, rods, castings, forgings, and extrusions are inadequate as to absolute amount, and inadequate with respect to relationship between the various sizes, shapes, and type of material. To make an aircraft wing there must be a specified amount of sheet, tube, bar, and rod. Sheet is not much use without the other items. Similarly, steel-carbon bar and plates may be available but a tank cannot be completed unless a specified amount of alloy-bar stock is also available.

The solution of this situation rests on a combination of factors: better control of the flow of material, additional output of critical raw and semiprocessed basic materials, more substitutions, and reduced use of these critical items in other than essential cases. A good job in each of these factors is fundamental.

Brigadier General W. H. Harrison

SUBSTITUTION AND CONSERVATION

I am touching on substitution and conservation because I think this is the field in which the engineering groups can be of most help. Conservation and substitution today do not mean that original designs were faulty. A part designed to be of aluminum may be the most efficient and effective, but with the pressure for aluminum for airplanes, we cannot afford to use it on ordnance parts, consequently we shift to steel, malleable iron, or some other less critical metal.

Again, a fuse part designed to be made of brass may be the ideal, but with the pressing need of brass for more essential uses, we find ways and means to make the fuse partly of steel or iron and partly of plastic.

Turning to another field, the extreme need for shipping space concentrates attention upon every form of package or packaging, first, to save shipping space, and next, to save the material used in the package.

This intensified drive for conservation has brought about amazing results. For instance, a primer tube originally designed to be made of brass is now made of steel. With millions of such tubes to be produced, the saving of brass runs into thousands of tons. A cartridge tank, originally of aluminum, is now made of steel and it is estimated the saving of aluminum is enough to build 500 bombers. A booster adapter, originally cut out of bar stock, is now made on presses, with a saving of thousands of tons of steel, and countless machine tools and man-hours.

Cartridge cases have always been made of brass, high-grade brass, the ideal substance for this purpose. The requirements of a cartridge case, that it expand sufficiently at the mouth to prevent the passage of gas, that it be strong enough at the base to prevent it from expanding and sticking, and that the primer parts should have the same coefficient of expansion as the case, all point toward brass. With insufficient brass we must turn to large-scale production of steel cases in all sizes. This means intensive research, experimentation with various kinds of steel, drawing, heating, and finishing operations, then extensive field-service tests and trials.

In the efforts to accelerate the program of conservation, we are trying to avail ourselves of every particle of information obtainable from our allies and our enemies. Everything captured or received from the enemy is subjected to searching analysis, and on the whole, there is little to indicate use of inferior materials.

Every department of the Services of Supply has its special consultants, and in turn the knowledge and experience of each department and the knowledge and experience of each manufacturer in a given field is brought to bear on the others. As to be expected, most intensive work is in the field of ordnance, and here startling things have been done. Booklets, copies of which are available, tell in an intriguing way about this work.

Recently the Chief of Ordnance canvassed all his contractors for suggestions. Some 1,100 were received, 60 per cent of which are being put to effective use.

THE ENGINEER'S PART

In conjunction with the War Production Board the Services of Supply are urging that engineering societies band together in common purpose to help with this fundamental job which is yet to be done. I have attended many joint meetings throughout the country and can attest to the constructive interest being taken and the fine work being done.

As a member of the engineering profession, I take modest pride and satisfaction in the part the engineers are taking in this war effort. Despite the fact that as in all wars, the brunt of this one must be carried by the men on the combat fronts and on the field-supply lines, nevertheless, this is a war of research, of engineering, and of equipment. Victory will be with us because we have the best fighting men in the world, because they are equipped with the best weapons on the field, and because banded together the citizens of these United States have determination to see this war through to their way of peace. Give the men of the United States forces and the men of allied forces more weapons at the combat fronts, and they will soon write the victory march.

England—Its Civilian Protection and Industrial and Utility Operations in Wartime

DAVIS M. DeBARD

English industries, utilities, and civilians have prepared for protection against blitz attacks, have carried on during them, and have set about to repair damages after them with courage and determination. Pointing out their splendid spirit and accomplishment under war conditions, the author of this article suggests that we in the United States might well draft our pattern for wartime living and working along lines similar to theirs.

WHEN this war is over, a story of heroism and devotion to duty will have been written about the employees of the English industries and utility companies. Many employees have been killed in their line of duty, and a great many more have been injured. When their homes were bombed during the night, the majority reported on time for work the next morning. When their families were evacuated from London and other congested areas, they remained to carry on. The trials and triumphs of British utilities as they have daily gone about their task of maintaining service to their customers in thickly populated areas and to the war industries under the constant destruction of the Nazi blitz is another story which we shall read some day with great pride. The English people, as a whole, living under a strain such as few people in the world have ever known, have gone forward with indomitable spirit, but we should all be especially proud of the devotion to duty of our fellow workers across the sea who have maintained service under the most trying conditions.

PROTECTIVE MEASURES

When the English industries and utilities found that war was inevitable, what did they do for their protection?

First, after providing additional guards, establishing the pass system of employees, fencing property, and erecting protective walls, they set about to train their employees, from office boy to president, in just what part they must play when their plant and distribution system suffered from fire and bombing. I observed in August 1939 some of these training classes at the British Gas Light and Coke Company, field laboratory, the Watson House, located on the outskirts of London. Several hundred employees were placed at windows on second, third, and fourth floors of adjacent buildings while actual bombing in an open field was carried out on gas mains, which, after the explosions, set fires in a number of dummy houses. Valves were turned to shut off gas, and different methods of fire fighting were demonstrated, and repairs were started. This was to give the employees a first-hand picture of actual bombing conditions. It is very important to train the eye to observe the damage, the ear to get accustomed to the horrible sounds, and the mind to record plans for action. These demonstrations were carried on for many months and some 16,000 employees in one large company knew exactly the parts they were to play under actual bombing.

Second, various types of camouflage were used to make plants more difficult to spot from the air. This was worked out in conjunction with the British Air Force, which made observations at various levels. A new smoke and fog camouflage has been developed that will blot out a blast furnace, an electric plant, or gas plant, from the air pilot's vision within a few minutes' time after the first flash of air-raid signal. All local city smoke abetment ordinances have been rescinded in England for the duration.

Black-outs, which from the outbreak of war have been complete black-outs—all night, every night, every place—are enforced in homes, stores, factories, and power stations by total screening of windows, skylights, doors, and other apertures against the egress of light from within. Full inside illumination is encouraged. Darkness inside buildings, in addition to being very bad for morale, would hold up production.

Third, electric distribution systems were sectionalized, with a number of connections to main source, and all isolated generating plants in the area were required to be interconnected with the central station system in order to furnish current for hospitals and other emergencies. Gas distribution systems were interconnected with other gas companies wherever feasible. Utility interconnections so widely used in America have proved of great value in maintaining service during the war in England.

The following data were received from the manager of the Metropolitan Water Board of London, which supplies water to approximately nine million persons in an area of 537 square miles. The system has over 8,000 miles of mains supplying 300,000,000 to 400,000,000 gallons of water per day to its users. The source of its supply

This article presents the essential substance of an address delivered at a meeting of the AIEE Philadelphia Section on November 9, 1942.

Davis M. DeBard is vice-president of Stone and Webster Service Corporation, New York, N. Y.

is two thirds from the Thames River, one sixth from the River Lee, and one sixth from hundreds of deep wells. Over 80 per cent of the water used is derived from polluted rivers. Mains under 12 inches are called small and those above, large. Large mains are usually fed from both ends.

Reservoir filtration plants, pumping plants, and distribution systems are divided into 20 separate areas. The operations of all areas are controlled from a central operating point. The usual method in prewar days was:

1. Storing in reservoirs.
2. Filtration through sand filters.
3. Chlorination.

Because of war conditions and the great demand upon the water system for fire fighting and drinking purposes, another precaution has been added, that of prechlorination.

What has been the effect of bombing on this system? The fracture of water and sewer mains by high-explosive bombs constitutes the greatest danger—pollution of drinking water—that the water companies have been called upon to face. Polluted water can be more dangerous than bombs or bullets. To date, because of the efficient operation of the water and sewer departments of this great London metropolitan system, practically no typhoid has resulted from breaks caused by bombing. Bombs of 500 pounds when striking a concrete street will crack cast-iron pipe to a distance of some 50 feet from the point of contact. It seems to flatten and break steel pipe at the joint, but London has comparatively little steel pipe.

Experience has shown that in most every raid there are one or two breaks, and it has also shown that in raids of two hours, or more, a number of so-called large water-main-pipe breaks always have occurred. Literally during the past two years in London hundreds of breaks have occurred where sewage and drinking water pipes have been broken at the same time. For example there was an instance in which a crater was filled with a mixture of sewage and water. The main, which fell away downhill from each side of the crater, was isolated by valves about a quarter of a mile distant on one side and three quarters of a mile on the other.

The main was shut off and it was found that the crater rapidly filled with sewage. This was kept down by pumping during the day, but at night pumping was not permitted and the trench filled with sewage, which poured into both ends of the water main. When the repair was nearing completion, one leg of the main was emptied through an emptying valve and the other leg was drilled for a corporation cock immediately in front of the charging valve. This leg of the main emptied itself through the hole made. When the repair had been completed, chlorination was started and a good dose put in before the charging valve was opened. The administration of chlorine was continued until its presence could be demonstrated at the bottom of the opposite leg and the main was fully charged with chlorinated water.

As this was a case of pollution in extreme degree and the main was known to contain large quantities of particulate matter, the usually short contact time was extended to several hours. A sample drawn after the main went back into supply gave the following result: bacteria coli in 100 milliliters, nil.

Large mains, and particularly trunk mains, present a very different problem; sewers broken by the same bomb may be wholly or partially obstructed, and widespread flooding with polluted sewage may occur; valves are present only at considerable intervals, and the volume of water to be treated with a heavy dose of chlorine demands a larger quantity than could be conveniently handled as a powder or solution. It was decided that the injection of a solution of chlorine derived from cylinders of liquid gas would be the only practicable method for applying the desired treatment, despite the possible risk of cylinders of chlorine in the streets. Consultation with the suppliers of liquid chlorine indicated that the risk of serious escape of gas would be small and would be unlikely to result from any cause other than a direct hit by a bomb. Cylinders should not be left in the streets at night.

Comparatively little damage has been done to the pumping plants and filter beds.

What methods were put into effect for the protection of property and the supply of water? After buildings have been damaged, where it is at all possible, the basement is cleared and sealed and filled with a supply of water as an emergency system. Many swimming pools and a great many cisterns have been so constructed. Each individual is supposed to keep on hand at least three-days' supply of bottled drinking water, and there has been provided for each district a number of 500-gallon water tanks which can be rolled upon trucks quickly, taken to prescribed places, and filled (not from hydrants on account of the danger of pollution). Deliveries are then made to the householders at the rate of about one gallon per person per day. Loud speakers attached to trucks are used to drive through the streets and warn the people of any pollution that might be in the water. They are instructed to boil the water.

The main precaution is that of prechlorination, which has added a fourth line of defense to the three that previously existed; namely, storage, filtration, and terminal chlorination. Chlorination instruments and pumps have all been protected against damage, many of them by the construction of specially designed bombproof buildings.

Each district has been provided with chlorine gas tanks fitted on trailers. These can be brought quickly to any broken main. The automobile could then return for an additional trailer if found necessary. The water departments were quite skeptical about these gas trailers, but little trouble has been experienced with

them from other than a direct hit. The British Government has been quite strict in keeping any of the towns from discharging any treated seepage into the Thames or Lee Rivers. This is to keep the pollution as low as possible, so that when excessive amounts of water are needed to fight fires, filtering and prechlorination will keep the water from being contaminated.

Essential repair parts are kept in all districts in bomb-proof shelters, and six-ton portable tractor-type cranes have proved invaluable. Before the war the Metropolitan Water Board purchased some 350 bicycles for use in air raids. These are used continuously by messengers, firemen, and others. The work could not have been carried out successfully without them. An organized emergency service, constant guarding of all reservoirs, testing of water at different locations, and experienced repair crews have all proved their value. Too much cannot be said for the loyalty and self-sacrifice of the chlorine and laboratory staff, who have worked through long hours of air raids, frequently during the night under long bombardments, together with repair crews, pumping crews, and the entire staff of the water works, for their valor under fire and for their superb protection of both health and water supply, that London should never burn nor its people be affected by disease.

Top water levels in certain large reservoirs have been lowered as an emergency measure in order to reduce the risk of flood and consequent damage to adjacent life and property in cases of bombed outlet.

A single pump may run long hours totally without any other connection except that between different tank mains, and this can offset to a large extent the effect of any single break. But the cumulative effect of fractured mains and possible heavy demands for fire fighting can reduce pressure in the mains to zero or cut off the supply entirely. Failure of water pressure at chlorinators has been alleviated by the installation of suitable pumps used at key points.

PROTECTION OF PROPERTY

In order that production may not be delayed unduly, in cases of bomb damage, most electric and gas utilities and industries also, have a supply of essential spare parts for their machines stored in bomb proof shelters. After two years of bombing, it is reported that repairs have been made with such speed that comparatively few electric and gas customers are without service within a 24-hour period.

Sand is kept available in buckets and in half-filled bags to extinguish fire bombs, and there is the stirrup pump, which, when used in conjunction with a bucket of water and hand operated, throws a small swift stream of water.

Although bombs have pierced many gas holders, causing loss of gas, they have not caused explosions. Some holders have caught fire, but fires were extinguished speedily. Holders can be repaired quickly. One has had 256 patches, and has been put in operation again.

Telephonic communication is extremely vulnerable to air attack. Many companies have strengthened their communication systems by using two-way radio, additional direct emergency telephone service, and, other types failing, an organized messenger service. This messenger service has proved its value many times. Radiobroadcasting stations are not used for air-raid alarms or precautionary instructions. The band just plays on. People might be excited and panics might be caused. Courage and keeping one's head are vital during fires and bombing raids. Calmness and forethought are just as vital to civilian defense, as black-outs or air-raid shelters, and they cost nothing. A series of light signals are given to industries before sirens sound. Roof spotters sound local horn or loud-speaker when air raiders are approaching the plant. Employees are used in shifts during the night for fire spotting. From all accounts, very few electric and gas plants have been put out of commission. The damage done by bombs has been speedily repaired.

In the great bombing of Coventry, the gas works was hit four times but never ceased production. Service was restored in some cases by laying pipes on top of the ground a short time after the all-clear signal sounded. The manager of the Coventry gas plant jokingly said that with just a few more well-placed bombs, he would have a much-needed new plant.

The following is a quotation from a recent English letter:

> Steel buildings stand up well. The brickwork panels get blown in or sucked out; doors, windows, floors, and roofs get displaced; but the main framework is seldom damaged. Brickwork supporting heavy weights is particularly dangerous. One side gets blown in by blast and the whole structure collapses. Under blast, tiles and slates depart like chaff in the wind; hence, considerable stocks of roofing sheets of galvanized steel or cement asbestos boards, and rolls of rubberoid roofing material are useful to have on hand under blitz conditions.

Bombs of from 100 to 500 pounds will make craters in the streets from five to ten feet in depth. Water, gas, and sewage pipes will be broken at a distance of from 30 to 50 feet from the point of direct impact. This is caused by the earth shock. After a study of utility reports on the effect of some several hundred different bombings of utility property, it is amazing the small amount of damage that was done and how speedily the repair gangs were able to restore service.

Antiaircraft shrapnel does not pierce the tops of gas holders or oil tanks, although it may injure roofs. Bombs when exploding are said to scatter into about 2,000 to 6,000 pieces. The most destructive bombs are the 2,000- to 8,000-pound land mines which float down on a parachute, exploding on earth's surface. These will level as much as four city blocks.

English buildings are made of brick largely, and many of them have been standing for hundreds of years.

These buildings have been subject particularly to lateral bomb shocks. Such buildings as have been framed with steel, similar to those commonly used in the United States, are little damaged. Records show a 500-pound delayed-action bomb which is about the size of a man, falling from 15,000 feet or more, will penetrate the roof and some five stories of a steel and concrete building having six-inch concrete floors, if it does not strike a beam or girder. Thus, one would be fairly safe during an air raid in a building more than six floors down from its roof. Steel girders seem to give and bend under bombing and only the walls and partitions are damaged.

From all reports, factory production has not been greatly harmed by the blitz. One report claimed that after the bad bombings, production had only been affected by five per cent. When factories in congested areas are damaged, they are moved to country areas and constructed in smaller units, thus lessening the risk from air. One airplane factory is reported to be in operation 90 feet underground. Parts for tanks are being made in 6,000 small factories and assembled in large factories. From all we are able to learn, production of war materials is at a very much increased rate over that of six months ago.

All important contracts and documents held by industries and utilities have been triplicated and filed in three separate areas for protection. Vaults are protection against fire and theft, but are not a protection against aerial bombs. This, in itself, must have been quite a problem.

In addition to the explosive bombs, one of the greatest problems is the magnesium fire bombs which weigh about $2^1/_4$ pounds each. One airplane can carry about 1,000 of these fire bombs. In falling from the enemy airplane at high altitudes, they are of sufficient weight to puncture the roof and explode in the attic. The molten substance scatters and spreads, making a very difficult fire to fight. In England it is recommended that attics be cleaned of any inflammable material and two inches of sand be placed over the floor of the attic. British houses are constructed of brick, whereas American houses are largely of wood. A thousand magnesium bombs dropped by the enemy in England are estimated to start 75 fires. In America the estimate is 150 fires because of wood construction.

A flying squadron of carpenters repair or condemn all bombed houses in England. More than 70,000 homes were repaired in one week's time during September 1940.

THE CIVILIAN'S PART

The worker, besides his regular duties of trying to take care of his home and family during air raids, is subject to fire-spotting duty, or auxiliary fire fighting, first aid, the home guard, or air-raid-warden duty. No compensation is given for any of these jobs except that on a fire watch during the night, a free breakfast usually is provided. Two out of every three persons between the ages of 14 and 65 are working full time in either the armed forces, civilian defense, or war industry in England. Single women between the ages of 19 and 31 are drafted for all types of war work. Married women between the ages of 20 and 45 are drafted for fire-spotting duties. Activities of children between the ages of 11 and 18 are directed to training that will eventually prepare them for a place in the war effort. The blind girls and boys are now being used in war factories for winding coils and other operations, with a surprisingly high degree of efficiency and accuracy. Industrial employees who are color blind are wanted as observers by the Royal Air Force. They can see through enemy camouflage. Camouflage is said to be no barrier to the color blind.

Labor has been co-operative to the point that strikes practically have been eliminated during the emergency. Small differences have arisen but have been adjusted quickly. Differences are settled in prewar manner by conferences. If this fails, the matter is brought up to the arbitration board whose findings are final. The hours of labor have increased from 40 and 55 to 56 and 60 hours per week per worker. Minimum office hours are 46; minimum factory hours are 52. Total earnings thus have increased approximately 30 per cent, largely because of the additional hours worked. Some 3,000,000 out of 18,000,000 workers' wages are adjusted by the cost of living index. The latest report shows that the cost of living has increased about 30 per cent, the same as the workers' income. It has been found that workers can produce more by having one day off in seven.

Retail store business has been curtailed, releasing 250,000 persons for war work in the past 14 months. Approximately 55,000,000 square feet of floor space have been liberated for more essential activities.

RATIONING AND TAXES

The present level of food rationing allows each person the following amounts of food per week: one egg; two ounces of butter; six ounces of margarine or cooking fat; eight ounces of sugar; eight ounces of cheese; two ounces of tea; approximately 20 cents' worth of meat. Canned goods, cereals, dried fruits, rice, barley, and so forth, are rationed over a four-week period according to a point system. For a month this allowance would be, per person: approximately one pound of prunes; one pound of rice; one box of cereal; and one quarter of a tin of grade-*A* salmon. Vegetables have been quite plentiful this year. One hears many complaints over the sameness of the food. Soap is rationed at three ounces per person per week. Coal for heating is rationed. The proposed reduction will be about $12^1/_2$ per cent.

Taxes are extremely high. A single worker earning $2,000 pays a total of $625 in income tax. A worker earning $3,000 pays $955 in tax. A married man earning $2,000 pays $505 in income tax. The tax is deducted weekly from wages. A part, approximately

20 per cent, of the yearly war tax will be returned to each person after the war. The amount of credit shall not be more than $260 per year per worker. In the last English budget the standard rate of income tax was raised to the all-time highest level of 50 per cent with reductions in the amount of existing allowances. Excess profits tax is now 100 per cent. Therefore, no profit can be made during the war. This is one of the steps taken by the British Government to safeguard against the risks of inflation. Another was the introduction of the coupon system which strictly limits the amount of food and clothing which may be purchased.

There are 51 clothing coupons for each man and each woman per year: man's suit 26; shirt 5; shoes 7; woolen socks 3; ladies' suit 16; pajamas 8. But the women are not giving up 8 points for pajamas. The only thing that is not rationed is the material for black-out curtains. They are making their pajamas out of this material. Pajamas made out of black-out material blend in with the night in case one has to leave the house quickly.

Electric and gas home-service departments have played a very active part in demonstrations and in publishing cooking recipes for the better use of rationed foods. They have also taken an active part in the setup of emergency canteens and cooking centers. The English people have not taken kindly to these cooking centers as they prefer, when it is practicable, to eat at home or in smaller groups. However, the British restaurants which serve cheap meals (250,000 daily) are very popular, especially in defense towns. The Ford Motor Company recently made a donation to England of $1,000,000 worth of portable kitchens which can be transported quickly from one locality to another when needed. At the beginning of the war much food and grain was stored in underground cellars, particularly prepared for this pupose.

CONCLUSION

The population lives in danger of poison-gas attacks. Continual training and preparation is being conducted to meet such attacks. With all of these problems the utility workers continue to maintain service, and the people of England continue to carry on with an undaunted spirit. Thus, life goes on with a courageous people.

Speaking of morale in England, Charles F. Palmer, former co-ordinator of United States Defense Housing, who returned via clipper, May 19, 1942, from a two-months' survey declared, "To have worked as intimately with the British as I have during the last two months is to know that Britain is waging war with all her might, with every factory, business, and home; with every pound, shilling, and penny; with every man, woman, and child. We cannot do less in America. Nothing else can win."

On completing this survey of the activities of the English in the face of a great crisis in which our colleagues are playing their own heroic role, one's mind travels quickly back across the Atlantic to the United States, which is speeding an all-out war effort.

At present one cannot conceive of Americans being subjected to the same type of blitz that has been England's lot to suffer. However, here in the United States we are liable to be subjected to token air raids for the purpose of creating fear and destroying morale. Our enemies are liable to try other types of military, incendiary, and germ surprises. Against such attacks greatest civilian protection in the United States is training—training of all employees, men and women, for just the part they must play in defense. Organization and training by local defense councils of sufficient personnel to meet all such emergencies likely to arise is desirable. Such organizations can be easily expanded where a nucleus of a trained group exists in each division.

Thorough training in first aid, fire fighting, air-raid-warden duty, emergency canteen work, ambulance service, all types of auxiliary and information service, set up by and directed by local defense councils are the greatest of all civilian protective measures.

The following is an excerpt from a letter from Miss Caroline Haslett, in London:

> On September 7, 1940, German bombers began a determined assault on London. And London, scarred but unshaken, found that the civilian arrangement made during the long months of quiet stood up to the test of war. Plans rehearsed a hundred times in dummy air raids were carried out amid the dust of fallen buildings and the glare of burning Dockland.

Here are some points that Americans well might consider regarding the waging of the war:

1. We can lose this war.
2. We have not been outfought to date, but outproduced and outmaneuvered.
3. Only arms, armies, and action count today; wealth, prestige, and $100 bills as such will not stop a tank.
4. Give the American people the facts about just what is going on; and, above all else, to tell the people the truth with the bark on it straight from the shoulder. There must be no mental coddling for the public.
5. Will it not take a long time to lick the Germans and Japanese working less than 24 hours a day, 7 days a week when, they, the Germans and Japanese, have been secretly preparing for war for years and years?

To quote Rear Admiral Marquart, "These are days of terrible war with no quarter given. Never before in our whole history has there been such a grave challenge to our country and our people, nor has our national life been in such dark peril from powerful, ruthless, and treacherous enemies."

Since December 7, 1941, we have been aroused; we have been united; we are confident that nothing will sway us from the defense of a country and the social, economic, and political principles in which we all believe.

We cannot escape nor would we escape from believing

in and fighting for the ideals which have made us free men and women of the United States of America.

Half way through the brief history of our own country, Lincoln expressed in his own simple, direct way what should be the universal prayer of us all. He said, "Let us have faith that right makes might; and in that faith, let us to the end, dare to do our duty as we understand it."

The Electric Pasteurizer

JOHN I. HALL
ASSOCIATE AIEE

The development of pasteurization is traced in this article from the experiments with wine by Louis Pasteur to the modern methods of milk pasteurizing—the holder and the high-temperature short-time methods. In the latter method electricity or hot water is used. Control, vital to the success of the process because of the necessity of holding the temperature within very close limits, is discussed in some detail as it operates in the present-day electric unit.

THE term pasteurization today applies to the process of heating every particle of a liquid to a temperature of 143 degrees Fahrenheit or more and holding at such temperature for not less than 30 minutes, or to a temperature of 161 degrees Fahrenheit or more and holding at such temperature for not less than 15 seconds. These standards have been established by the United States Public Health Service and have been termed the holder method and the high-temperature short-time method, respectively.

THE HOLDER METHOD

In the modern holder method a jacketed vessel of about 100- to 300-gallon capacity contains the milk which is brought up to pasteurizing temperature by spraying water of a controlled temperature down the outside of the vessel. This water is heated by steam injection which can be controlled either manually or automatically.

The limitations of this method are:

1. Without regeneration, which is a rather expensive item for the small dairyman, there is a loss of heat.
2. The transfer of heat to the metal wall frequently is inefficient because of conditions of film movement.
3. Certain nutritive values are affected.
4. The process is subject to human error.
5. Time and equipment are required, since it takes about one hour to process the supply in the vat.

THE HIGH-TEMPERATURE SHORT-TIME METHOD

In general, the high-temperature short-time pasteurizing equipment can be divided into two groups so far as the method of heating the liquid is concerned; one group uses electricity, the other employs hot water.

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The electrical type consists essentially of a plate regenerator and electrode chamber. The regenerator is made up of thin stainless-steel plates which are hung on parallel supports in a frame so that while the edges of a series of plates bear upon each other, the bodies have a small clearance between them. Thick rubber gaskets inserted in grooves around the edges of the plates form a water-tight seal. The frame is fitted with a screw press which holds the plates tightly together. In operation a continuous stream of milk is forced between the sections of adjacent plates.

In an installation, the plates are arranged in two sections as follows:

1. A regenerator section in which cold raw milk is sucked or forced between certain plates and the hot pasteurized milk is forced in the reverse direction between the adjacent plates.
2. A cooling section in which a refrigerating solution is forced between certain plates while the milk is flowing in the reverse direction on the opposite side of these plates.

The pasteurizing process in this machine is shown schematically in Figure 1 and a description of it follows.

Raw milk initially at a temperature of about 50 degrees Fahrenheit is brought to a temperature of approximately 132 degrees Fahrenheit in the regenerator section. It then flows through the electrode chamber where its temperature is raised to 162 degrees Fahrenheit. After passing through a holding tube which maintains the milk at the critical temperature for not less than 15 seconds, it passes again through the regenerative section where it gives up part of its heat to the incoming raw milk. The temperature of the pasteurized milk is lowered to about 70 degrees Fahrenheit; thereupon it enters the cooling section where it reaches its final temperature of 50 degrees Fahrenheit or lower. It then passes directly to the bottler, after which the filled bottles

are crated and stored in a refrigerator. The process is one of continuous flow and requires a total of only 80 seconds for the complete circuit.

The single-phase electrode chamber, where the final heating occurs, is 12 inches or more in length and of a rectangular cross section. Two sides of the chamber consist of carbon electrodes separated by insulators which form the other two sides of the chamber. Current flows through the milk itself as in a water rheostat and causes sufficient heating to raise the temperature to that required for pasteurization.

It is generally agreed by authorities that the destruction of bacteria by this method is caused by the heating of the milk and not by the effects of the current or voltage.

The hot-water method of heating uses the plate-type regenerator and cooler as described, but differs in that another plate section is added where hot water is forced between certain plates and the milk already warmed in the regenerator is heated to the pasteurizing temperature between adjoining plates.

The high-temperature short-time method of pasteurization has several operating advantages which are:

1. Economy by the conservation of heat.
2. Complete enclosure of the system.
3. Reduction of space occupied by equipment.
4. Reduction in labor required.
5. Greater conservation of nutritive values in the milk (vitamin *C*).
6. Prompt operation.

HISTORY

The troubles of a poor wine maker led Louis Pasteur in 1857 to experiment with the effect of heat in checking the fermentation of wine. These studies were later extended to milk. In 1865 Pasteur announced to the Academy of Science that the maintaining of wine for a few minutes at 140 to 158 degrees Fahrenheit kept wine from spoiling.

In 1893 the first large demonstration of pasteurizing milk was made in New York where the milk was used for infant feeding, but commercial pasteurization did not begin until about 1900. Investigators since that time have found that a temperature of about 143 degrees Fahrenheit maintained for a period of 30 minutes will kill all the harmful bacteria in milk. It was also found that there is a definite time-temperature relationship which led to the establishment of the high-temperature short-hold value of 161 degrees Fahrenheit for 15 seconds.

Early electrical pasteurization was performed in England by J. M. Beattie and F. C. Lewis in 1911, where alternating current ranging between 2,500 and 6,000 volts was used. The apparatus consisted of a horizontal glass tube through which milk flowed continuously, passing through copper electrodes, one at the middle and one at each end. The success of these experiments resulted in the development of electrical pasteurization on a commercial scale.

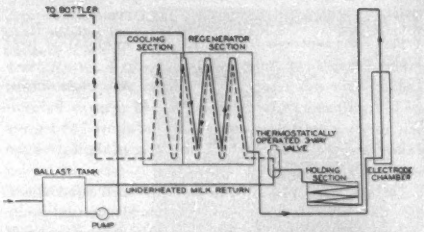

Figure 1. Flow of milk in electric pasteurizing machine

In 1914 two electrical pasteurizers were in operation in the United States, consisting of a series of porcelain cups containing electrodes with the circuit completed by the milk stream. An investigation of this type of unit in 1919 pointed out that an improved temperature control was needed, a device to assure a uniform heating, and a means to prevent underheated milk from being bottled.

Around 1920 a rectangular electrode chamber consisting of two carbon electrodes separated by suitable insulators appeared. Commercial 220-volt 60-cycle current was used and the temperature control consisted of a hand-operated micrometer valve at the entrance to the electrode chambers. A regenerative heater in which the raw milk was heated to about 120 degrees Fahrenheit by the hot pasteurized milk flowing over the outside of tubes carrying the raw milk was also used on this equipment. In 1926 two additions were made to this type of pasteurizer:

1. A constant-level tank to maintain a constant head on the centrifugal pump.
2. An automatic temperature controller to control the speed of the milk pump thereby regulating the temperature at which the milk was treated. The hand-operated valve was maintained for a rough adjustment.

In 1930 there was added a thermoelectric device to stop the milk pump should the temperature of the heated milk drop to any predetermined level. The importance of holding the temperature of the milk at a predetermined value was also emphasized, thus removing high-temperature pasteurization from a flash method to the high-temperature short-time method.

In 1937 there appeared a new unit which incorporated a constant rate of flow, an automatic means of varying the voltage at the electrode chamber to maintain a constant temperature of the milk, and a contact thermometer to stop the milk pump should the milk drop below a predetermined temperature. Subsequent changes in this equipment since that date have been the replacement of the pump-stop method by an automatic valve which returns underheated milk to the raw supply, and a plate-type regenerator or heat exchanger. A modern pasteurizing unit is shown in Figure 2.

THE CONTROL CIRCUIT

For successful pasteurization, it is essential to heat every particle of milk to the required temperature and to hold this temperature within very close limits, for if the temperature drops below 161 degrees Fahrenheit, the product is not pasteurized, and above 164 degrees Fahrenheit the amount of cream rising to the top of the bottle will be reduced.

Various step-by-step controls have been tried where the voltage across the electrodes is held constant while the rate of flow of the milk through the system is varied in response to variations of the pasteurizing temperature. The rate of flow is increased or decreased in steps as the temperature of the milk varies from the desired temperature. This control will therefore hold an average temperature close to the desired temperature, but certain sections of the milk will be overheated and the alternate sections, when the rate of flow is high, will be below the pasteurizing temperature.

Other controls have been tried where the rate of flow remains a constant and the heating effect changed in steps. With this type of control, also, because of its inherent insensitivity, the desired average temperature may be held, but alternate sections are either too hot or are below pasteurizing temperatures.

The ideal control for this type of application would be one of continuous modulation of the heating effect of the electrodes so that all sections of the milk stream will be heated to substantially the same temperature. Such control has been accomplished by employing a thermoelectric device which supplies a voltage proportional to the temperature of the milk, an amplifier which amplifies this voltage several thousand times, and a saturable reactor which regulates the voltage applied to the electrode chamber.

THE THERMOELECTRIC DEVICE

The thermoelectric device is a variable impedance bridge operated by a modulating temperature-control element which responds to the temperature of the milk. The impedance bridge has two input windings mounted on the outside legs of an E-shaped core as shown in Figure 3. These are connected in series with each other so that they set up a flux flowing in the same direction in each leg. Two output windings are also mounted on these legs of the core which are threaded by flux generated by the input windings and are arranged to oppose each other. A pivoted armature, which is operated by the bellows of the bulb-and-bellows temperature-response system, varies the amount of flux which threads the output coils by varying the air gap between the armature and core. When the two air gaps are equal, the effective output voltage becomes zero since the output windings oppose each other, but any unbalance of the flux which threads these two coils will result in the generation of an a-c voltage, the magnitude of which will depend upon the extent of the unbalance between air gaps. The core is also pivoted so that it can be adjusted, through a knob and cam, to obtain the proper relationship between the armature and bellows in obtaining the desired pasteurizing temperature.

DOUBLE CASCADED REACTOR CONTROL

The output of the impedance bridge is an a-c voltage which decreases as the temperature of the milk rises above the desired value. This voltage is rectified and the resultant direct current energizes the control coil of a small saturable reactor or amplifier. This reactor also has a bias coil which is energized from a power transformer through a full-wave rectifier. The current in the bias coil is adjusted so that it has less ampere turns than the control coil and operates in conjunction with the control coil. A decrease in the control voltage will decrease the saturating flux in the saturable reactor and decrease the a-c output. Across the a-c coil of the reactor is connected a rectifier unit to obtain a high ratio of control through regeneration, as shown in Figures 4 and 5.

The a-c coil of this reactor is in series with a full-wave rectifier which is energized from the power transformer. The d-c output of this rectifier is then a negative function of the milk temperature, for as the milk temperature increases, the output of the impedance bridge decreases. This output, acting on the control coil of the reactor, in conjunction with the bias flux, desaturates the iron and there is a corresponding increase in the reactance of the reactor a-c coil. This results in a larger voltage drop across the reactor coils and a lower output. As the temperature decreases, the action is reversed and the d-c output voltage increases. In series with this output voltage is another rectifier supplied from the power transformer which is an additional bias to limit the minimum d-c voltage.

This amplified voltage is impressed across the control coils of a large saturable reactor. The a-c windings of this reactor are in series with the electrodes of the

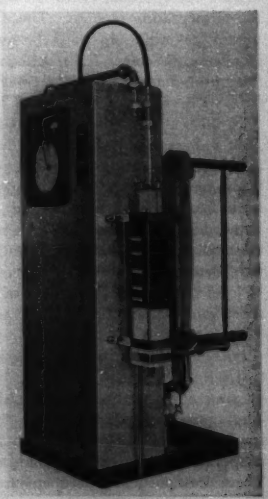

Figure 2. Electric pasteurizing unit, 1942 model, with cascaded reactor control and plate type regenerator

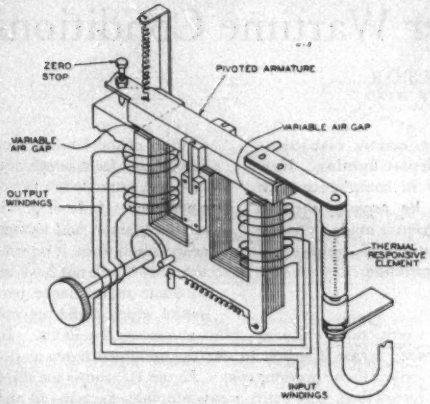

Figure 3. Variable impedance bridge

heating chamber and variation of the d-c voltage varies the a-c electrode voltage through a range of 230 volts (line) to a minimum of 140 volts. With a temperature increase of the milk, the direct current to the coil of the large saturable reactor decreases, the voltage drop across the a-c windings of the reactor increases, and the electrode chamber voltage decreases. Less heating of the milk occurs and the temperature returns to the correct value.

The large saturable reactor is of special design having two a-c coils on each leg of an E-shaped core, or four coils in all. These coils are connected so there are two a-c circuits, each circuit going through two a-c coils on

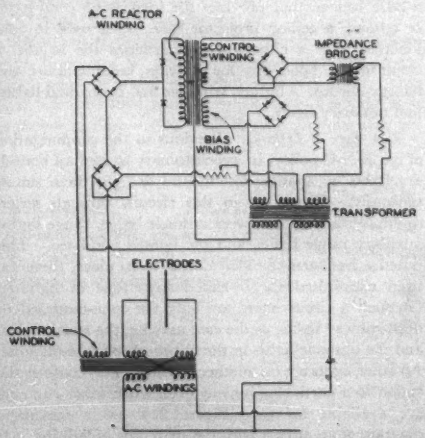

Figure 4. Wiring of cascaded reactor control

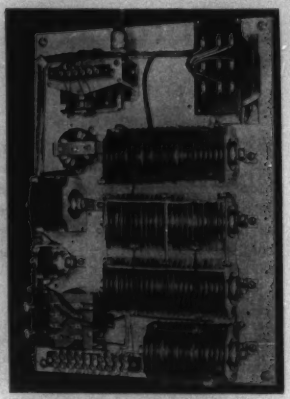

Figure 5. Control panel showing impedance bridge, first stage reactor, and rectifier units

opposite legs. By using this connection there is an equal voltage drop on each side of the line (providing the currents are equal in the two lines). Since the pasteurizer is grounded, and the center points of most 220 and 230 volt a-c systems are grounded, there is a possibility of ground current flowing, with consequent unbalanced currents in the two sets of reactor coils. If there were only two a-c coils, one on each side of the line, unequal currents in the two lines would induce an a-c voltage in the d-c control coil of the reactor. This would unbalance the system and change the heating effect on the milk. With four coils connected in the manner described, the fluxes in the two legs are always equal, no matter what ground current may be flowing.

SENSITIVITY AND AMPLIFICATION

After the proper adjustments have been made on the bias and control voltages in order to obtain the maximum degree of sensitivity without having the control overcorrect and so produce oscillations, the sensitivity will average about 18 volts per degree change in the pasteurizing temperature. That is, should the pasteurizing temperature increase one degree, the voltage across the electrodes will decrease 18 volts, thus decreasing the heating effect and restoring the desired temperature.

With these conditions the power amplification on the smallest unit is 14,000 to 1, whereas the larger units go as high as 60,000 to 1.

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Airport Lighting Under Wartime Conditions

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As a wartime expedient, certain restrictions have been placed on airport lighting. How the lighting of airports in compliance with these restrictions may be accomplished is explained here. Distinction is made between normal wartime operation of lights and black-out operation.

ONE of the more important changes deemed necessary by wartime conditions was that applying to the lighting of airports in "combat zones." In the past it has been the practice of lighting engineers to utilize all available lighting equipment commensurable with maximum visibility and safety. Now, however, the use of such equipment has been restricted, the reason for this being, naturally, that airport lighting should be available only to friendly aircraft.

These restrictions were formulated by the committee on airport and seadrome lighting, which is composed of representatives of the United States Army Air Forces, United States Navy Department, the Civil Aeronautics Administration, and the Bureau of Aeronautics and were drawn up in the form of a policy known as the Army-Naval-Civil Uniform Requirements for Operation of Aerial Lighting Aids.

THREE TYPES OF AIRPORTS

In so far as lighting is concerned, there are essentially three types of airports:

1. Strip-type fields using cone-mounted lights.
2. Strip-type fields using flush runway-marker (contact) lights.
3. All-way fields using flush contact lights.

The first type of field has strips of usable landing area which are 500 feet in width and generally composed of turf. The cone-mounted lights are placed along the periphery as shown in Figure 1(*a*). These lights serve a second purpose in that they also act as boundary lights for the safe landing area. The dashed lines show where paving can be placed if desired. Generally, however, this entails the installation of flush contact lights along the paving. Such a conversion places the field in the category of the second type of field which is shown in Figure 1(*b*). The use of the cone-mounted lights is optional. If used, they are placed along the dashed lines and serve as boundary lights. This type of field also has 500-foot landing areas, but there is a 150- or 200-foot paved runway in each one. The flush contact lights are placed along both sides of the runways. In some instances a 75-foot strip of soil-cement (a mixture of soil and Portland cement) bounds the paved runway. The area outside of the paved runway and within the confines of the landing area can be used for take-offs and landings, but only in cases of emergency. If the airport is relatively small and located near a small town, it is probable that it will not have an adequate maintenance personnel which could prevent weeds, dust, and snow from obscuring the lights. In such a case it is best to use cone-mounted lights as described in the previous case. Figure 1(*c*) shows the third type of field. The entire area is adaptable for take-offs and landings in all directions. This means that a suitable surface covers the entire field. However, it may have superimposed on it paved runways along which are flush contact lights.

Natural surroundings, soil conditions, climate, topography, number and height of structures, and air traffic are some important factors which determine a choice among the three types of airport lighting mentioned.

AIRPORT LIGHTS

In addition to the runway lights, all of the types of fields described have boundary lights, which are placed in strategic positions and so define the entire area of operations—obstacle lights that define danger zones; range lights that mark the extremities of runways; a rotating beacon that guides the aircrafts to the airport; a code beacon that provides the identifying code letter or letters; a ceiling projector that, when used in conjunction with a clinometer, determines the height of cloud strata; floodlights for runways, landing areas, and hangar aprons; a lighted wind tee and cone; taxi lights; and auxiliary lights.

Strip Type of Lighting. Previous to the promulgation of the A-N-C policy, it was customary to feed all boundary lights by a single circuit and so light them simultaneously. Connected to this circuit, through series-multiple transformers, were obstacle lights, range lights, auxiliary range lights, and the lighted wind tee. This practice has been abandoned and, in its place, there has been substituted the so-called strip type of lighting. On such a circuit there are only the cone-mounted or flush runway lights, as the case may be, the range lights, and the obstacle lights in the approach or take-off zone. All other lights are on another circuit. This confines the action to a particular runway even when other runways are available for use. Figure 2 shows a schematic diagram of an airport with the strip type of lighting. It is seen that all necessary lights are fed by one circuit.

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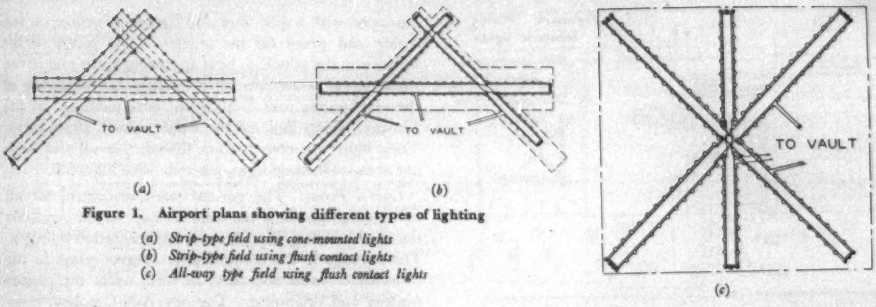

Figure 1. Airport plans showing different types of lighting

(*a*) *Strip-type field using cone-mounted lights*
(*b*) *Strip-type field using flush contact lights*
(*c*) *All-way type field using flush contact lights*

Operating Conditions. There are two operating conditions which are recognized under the A-N-C policy. They are normal wartime and black-out operation.

Normal wartime operation allows the use of the lighted wind indicator, the rotating airport beacon, and all turning-zone obstruction lights. Floodlights are not to be used except, possibly, in northern regions where snow may obscure flush contact lights. If the airport landing strips are lighted by cone-mounted lights, it is permissible to light all strips simultaneously. This is done by an all-on relay as seen in Figure 5. Paved runways require flush-mounted lights and are to be lighted only in the take-off or landing direction. Restrictive hoods which limit the horizontal and vertical visibility of the lights, except at the proper glide angle, are not required.

Black-out operation does not allow the use of any lights except those connected to the strip circuit. Placed over these lights are the restrictive hoods, which are shown in Figure 3. The hoods over the contact lights limit the horizontal visibility to 10 degrees to either side of a line parallel to the runway and the vertical visibility to 15 degrees above the horizontal.

Since the obstacle lights are generally mounted on trees, buildings, or poles, it is feasible to use duplex lights, each of which is equipped with a hood. One light faces the field and the other, away from the field as shown in Figure 4(*b*). All those facing one way are on one circuit, and those facing the other way are on another. Suitable switching arrangements accomplish the selection of the lights and eliminate the manual operation of reversing the hoods on single obstruction lights. Figure 4(*a*) shows a case in which a series-series isolating transformer is used, and Figure 4(*b*) shows the case for a series-multiple transformer.

The series-series arrangement shows that the switches are selective in that they can short-circuit the group of lights which are not in use. Both switches are closed when the particular runway is not in use. This also short-circuits the secondary winding of the transformer and prevents its operation with an open-circuited secondary winding. This arrangement is preferable to that shown in Figure 4(*b*) because of the inherent low power factor and low efficiency of a series-multiple transformer.

Brightness Control. The brightness of these lights is controlled by means of an auto-current-transformer equipped with taps and regulated by suitable relays. There are five taps, 100, 30, 10, 3 and 1 per cent of normal brightness. These steps are chosen with a brightness-selector switch which operates the brightness-selector relays. This is seen in Figure 5.

The range and obstacle lights are controlled simultaneously with the contact lights because all are on the same circuit. Runways with cone-mounted lights must

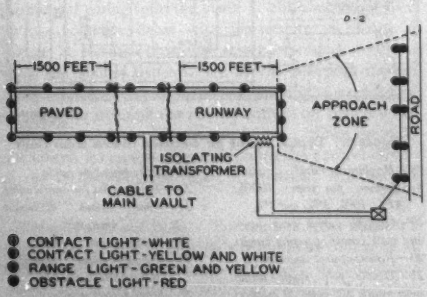

Figure 2. Strip type of lighting

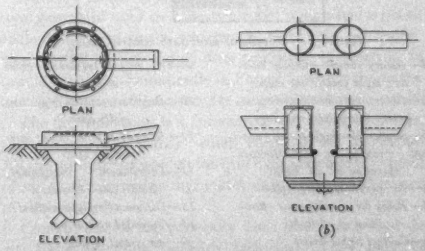

Figure 3. Lights equipped with black-out restrictive hood

(*a*) *Contact light* (*b*) *Duplex obstacle light*

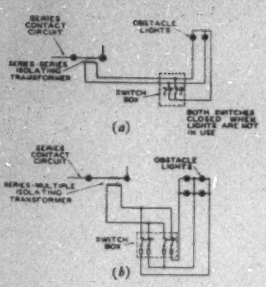

Figure 4. Wiring of obstacle lights

(*a*) *Series-series connections*

(*b*) *Series-multiple connections*

have an auto-current-transformer and a constant current regulator with a capacity large enough to carry all strips simultaneously, whereas, for paved runways having flush-mounted lights, the capacity need be only large enough to carry the largest strip circuit load.

Meaning of Colors. The color of the lights varies according to their location and each color has a definite meaning. In regard to the contact lights, those which are within 1,500 feet from either end of the runway have a split filter which shows clear from the approach end and yellow at the other end. The range lights are also equipped with a split filter and they show yellow on the inside and green on the outside. The yellow lights indicate to the pilot that he is approaching the end of the runway, and the green lights indicate the beginning of the safe landing zone. All other lights mounted on the runway, which indicate the runway itself, show clear. These lights, therefore, outline the safe take-off and landing area. Obstacle lights are red. See Figure 2.

Control Points. The normal point of control for all lighting equipment is the control tower which overlooks the airport and is located in the administration building. The switches in the control tower operate relays in the transformer vault and they, in turn, select the proper runway and brightness. The new A-N-C policy, however, requires an alternate control point located at least 150 yards from the control tower. The logical alternate point is the transformer vault which, preferably, should be underground.

Means are provided in the vault for either manual or electrical control. If manual control is desired, the control circuit from the tower to the vault must be opened by an operator in order to prevent the possibility of remote control from the tower occurring simultaneously with manual control in the vault. When remote control from the tower is resumed, care must be taken

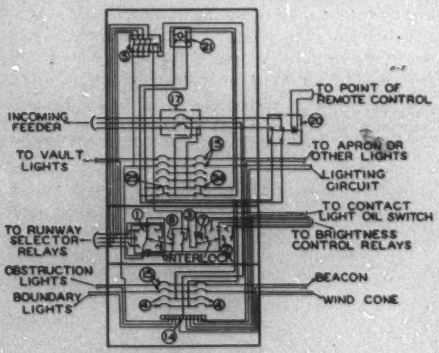

Figure 5. Details of alternate control panel

1—Rotary switch—runway selector; eight points, one stage
2—Rotary switch—brightness selector; five points, one stage
3—Single-pole-single-throw control switch—for simultaneous operation of all lights
4—Air circuit breaker; spare
5—Relay for simultaneous operation of all lights
6—Contact lights switch
7—Switch—lock—spring return to closed position
8—Fused cutout; porcelain enclosed
9—Oil circuit breaker; remote control
10—Brightness-control relay; normally open
11—Runway-selector relay; normally closed
12—Distribution transformer, 2,300/230–115 volts
13—Disconnecting-type pothead
14—Grounded neutral bar
15—Air circuit breaker
16—Bus—number 6 wire, 2,300 volts
17—Main switch or air circuit breaker; manual

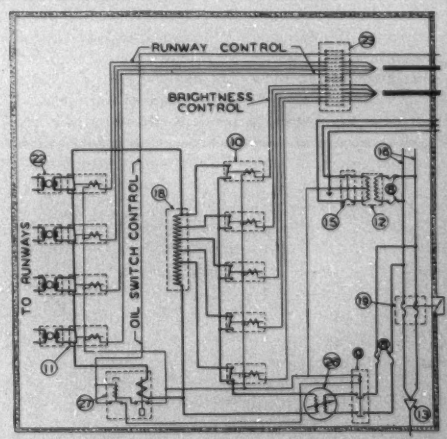

Figure 6. Typical wiring for electrical control from vault

18—Brightness-control autotransformer; five steps: 100%, 30%, 10%, 3%, and 1%
19—Oil-type cutout gang operated with remote operating handle
20—Remote-control contactor
21—Double-pole single-throw time switch 230 volts 30 amperes (minimum)
22—Series-plug-type cutout
23—Terminal box for control cable
24—Time switch disconnect (manual)
25—Control switch (manual)
26—Constant-current regulator, 6.6 amperes secondary
27—Series-protective relay

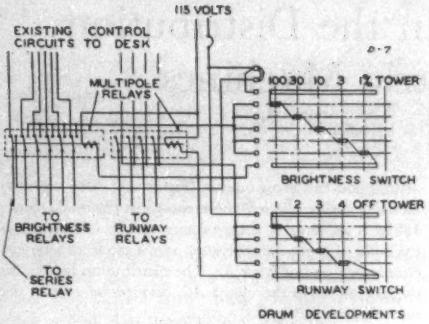

Figure 7. Connections of rotary switches

to leave the manual operating apparatus in the vault in the proper position.

The connections for manual operation are similar to those for electrical control except that hook-stick disconnect switches are connected in parallel with the contacts of the brightness-selector relay. One is needed for every tap on the auto-current-transformer. Only one switch is closed at any time and all are open when operating from the control tower. The runway is selected by blocking, in the open position, the contacts of the runway-selector relays. The changes in brightness and runways are made only when the circuits are dead. This, of course, is controlled by the primary oil switch which is also manually operated.

Electrical operation does not require an operator to disassociate the control wiring from the tower to the vault. This is provided for by transfer relays. The switches in the vault, however, must be set for control from the tower when such control is resumed. Figure 6 shows a typical wiring diagram for electrical control from the vault.

The number of poles of the two transfer relays corresponds to the number of control circuits from the control tower. When the relays are energized, they disconnect the control wiring from the tower. This is accomplished by two rotary switches with connections as shown in Figure 7. Control from the tower cannot be resumed until the rotary switches are at the position marked tower. The pull-out switch on the brightness-selector switch is for opening the remote-control oil switch when changing positions of the rotary switch. Since the pull-out switch is connected in series with the control circuit of the series-protective relay, it obviously controls the oil switch.

Control Panels and Desks. The main purpose of control panels and desks is to provide a centralized control of all lighting equipment. The size of airport, the amount of traffic, and the number of buildings available determines the type of panel or desk used.

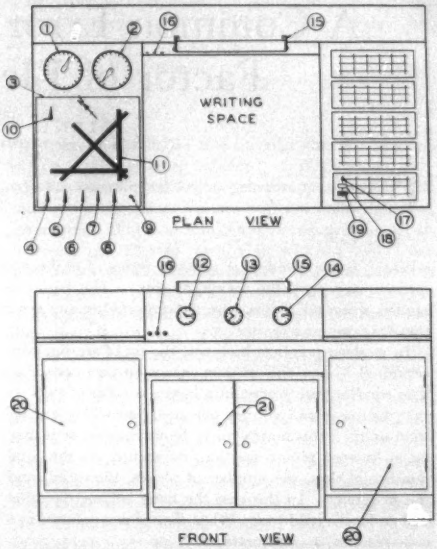

Figure 8. Typical control desk used at large airports

1—Wind-direction indicator
2—Wind-velocity indicator
3—Facsimile runway map
4—Contact-light master switch
5—Runway-selector switch
6—Floodlight master switch
7—Switch, lock, spring return
8—Brightness-selector switch
9—Tumbler switch for simultaneous operation of all runway contact lights
10—Controller pilot-light dimming
11—Runway
12—Barometric pressure (altimeter) indicator
13—Clock
14—Outdoor-thermometer indicator
15—Fluorescent desk light
16—Telephone and microphone plug bushings
17—Red pilot light, miscellaneous airport-lighting circuits
18—Name plate
19—Tumbler switch for miscellaneous airport-lighting circuits
20—Circuit-breaker and pilot-light relay compartment
21—Wiring compartment

Figure 8 shows a typical airport control desk of the type generally used in a large airport which has a glass-enclosed control tower and heavy nighttime air traffic. The control wiring of this desk conforms, in general, to that illustrated schematically in Figure 5, which shows the wiring diagram of the alternate control panel in the vault.

The facsimile map is a convenient aid to the operator, as it shows at a glance which runways are available. All the equipment needed for quick and adequate control of air traffic is within sight and easy reaching distance of the operator.

Control panels are generally used at airports that do not have adequate building facilities. They may be either of the indoor or outdoor type. In any case, they are basically alike in so far as centralization of control and wiring are concerned.

A Common Error in the Distribution Factor of Electric Machines

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THE basic equation for the voltage of an alternator or a-c motor is

$$E = 4.44 Z f \phi_m 10^{-8}$$

where Z is the number of turns in series, f is the frequency, and ϕ_m is the maximum flux. This equation applies when all Z turns are concentrated in the same slot or in one pair of slots.

In modern practice, however, the turns are not concentrated in one pair of slots except on rare occasions. The windings are placed in a larger number of slots, so that the number of slots per pole per phase will be greater than unity. This number may be an integer, or it may be an integer plus a fraction, depending on the total number of slots, the number of phases, the speed, and the frequency. In this case the basic voltage equation will no longer hold true. When the voltage induced in a coil reaches a maximum, then the voltages of the subsequent coils will be out of phase by an amount determined by the electrical angle between the slots. These voltages must, therefore, be added vectorially, and the total will be less than would have been the case if all turns had been located in one pair of slots.

A common error is often made in the use of the distribution factor of an electric machine when a winding consists of a fractional number of coils in series. This article discusses a quick and easy way of finding the correct value of this factor and a simple method for determining the best distribution of such a winding.

The ratio of the actual voltage to the voltage that would have resulted from the total turns, had they been located in one pair of slots, is called the *distribution factor*, k_d.

The equation now becomes

$$E = 4.44 Z f \phi_m k_d 10^{-8}$$

The distribution factor can be calculated by vectorially adding the voltages in the individual coils and dividing the result by their arithmetical sum.

SLOTS PER POLE PER PHASE AN INTEGER

In a machine with N slots, P poles, and m phases, there will be N/mP slots per pole per phase. The electrical angle between slots will be

$$\alpha = \frac{180P}{N}$$

The number of vectors to be added is equal to the number of slots per pole per phase, and is $s = N/mP$; by assumption this is an integer (Figure 1). The vectorial addition can be carried out as shown in Figure 2. Since $180/\alpha$ is an integer, these vectors can be considered as the sides of a regular polygon, and a circle can be circumscribed as in Figure 3. The distribution factor will then be equal to the chord AC, divided by s times the vector length AB.

It becomes

$$k_d = \frac{\sin s\frac{\alpha}{2}}{s \sin \frac{\alpha}{2}}$$

This equation holds true for any number of phases, but only when s is an integer.

Sin $s(\alpha/2)$ will be a constant for a given number of phases; it can be found to be sin $(180/2m)$. Figure 4 illustrates this for a three-phase system where each phase covers $180/3 = 60$ degrees.

The limit value of the distribution factor for different numbers of phases can now readily be determined by assuming an infinite number of slots per pole per phase. The polygon will then approach a circle, and the distribution factor will be equal to the chord divided by the arc over an angle equal to $180/m$.

For a three-phase system, the limit will become

$$k_{d\infty} = \frac{R}{\frac{180}{3} \times \frac{2\pi R}{360}} = \frac{3}{\pi} = 0.9549 \cong 0.955$$

For a two-phase machine, it becomes

$$k_{d\infty} = \frac{R\sqrt{2}}{\frac{180}{2} \times \frac{2\pi R}{360}} = \frac{2\sqrt{2}}{\pi} = 0.9003 \cong 0.900$$

For a single-phase machine

$$k_{d\infty} = \frac{2R}{\frac{180}{1} \times \frac{2\pi R}{360}} = \frac{2}{\pi} = 0.6366 \cong 0.637$$

Knowing these limits, we can tabulate the values of the distribution factor k_d for different numbers of slots

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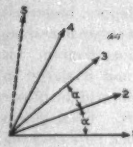

Figure 1

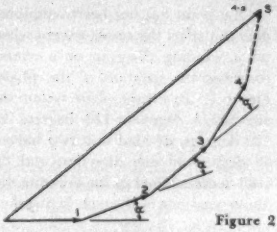

Figure 2

per pole per phase in Table I. Caution is required when these values are used for a single-phase machine, because they will not apply unless a full-pitch winding is used, and all slots contain equal live coils.

SLOTS PER POLE PER PHASE NOT AN INTEGER

It is not always feasible to use a whole number of slots per pole per phase. When a whole number of slots per pole per phase cannot be used, it is often possible to obtain a balanced winding with a fractional number of slots per pole per phase. It is possible to design a balanced winding with such a fractional value of s, if certain requirements are met: In order that the voltages of all phases will be balanced, each phase must contain an equal number of coils and, consequently, an equal number of slots, even though the number per pole will vary for the different poles. This can be stated as follows:

In order to obtain a balanced winding, it is necessary that the number of slots contains the factor m (equal to the number of phases) at least one more time than the number of poles contains that factor.

For instance, if the number of poles (12) contains the factor m (3) once (3×4), then the number of slots must contain that factor at least twice, that is m^2 ($3^2\times7$, or 63). This would make the number of slots per pole per phase $s=63/(3\times12)=1^3/_4$, and would give a balanced winding.

An error is frequently committed in the use of the distribution factor for a fractional number of slots per pole per phase. To a scientist, this error may not appear to have any justification, but an engineer can readily understand how it could happen to be made. A design engineer uses a table similar to Table I. An unsuspecting engineer is quite likely—though not justifiably so—to interpolate for a value of s between those given in the table. He is even likely to plot the values and connect the points by a curve, then reading the intermediate values from this curve. It will be shown that this is incorrect. Although in most cases the error will not be a large one, it may on certain occasions amount to several per cent. Since the distribution factor appears to the second power in some reactance calculations, the error may actually assume objectionable proportions. In order to analyze the conditions obtaining when s is not an integer, it is necessary first to consider what happens to the winding in that case.

Let there again be N slots, P poles, and m phases; in this case however $s=N/mP$ will not be an integer. Assume that c is the greatest common factor of P and N. The fraction then becomes

$$\frac{N/c}{mP/c}$$

N/c must be a multiple of m in order that the winding will be capable of being balanced. If N/c does not contain the factor m, the angles between phases will not be equal, and the phase vectors will not have the same magnitude. The fraction can now be written, when $N/c=ma$ and $P/c=b$: $s=a/b$, in which a and b are integers having no common factors. a/b is the slots per pole per phase, written as an improper fraction.

This greatest common factor c indicates the number of times that the same part of the winding is repeated. The section that is repeated contains N/c slots. This factor c, and any of its factors, therefore indicates the number of parallel circuits that can be used. A factor $c=6$ would show that 1, 2, 3, or 6 parallel circuits could be used and give a balanced winding. Each repeated section will cover P/c poles and will contain all phases. It is now necessary to determine the most advantageous manner of distributing this section over the poles and the phases. We can do this by writing numbers from 1 to N/c in a vertical column. These numbers represent the slots in a repeated section starting at an arbitrary point.

The angle between adjacent slots in electrical degrees will again be $\alpha=180P/N$.

The equivalent angular displacement between each slot and the first slot is now tabulated opposite the slot numbers. It is also possible to draw these vectors from a common center as in Figure 1. By either method it will be found that the vector which follows the last one

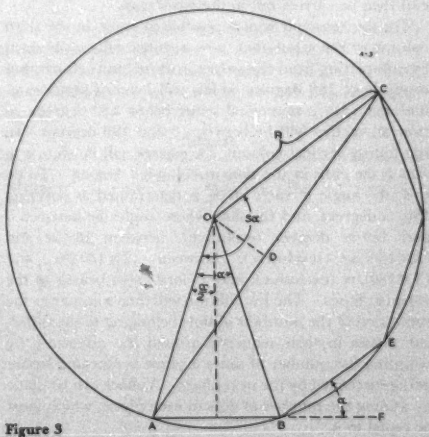

Figure 3

Table I. Distribution Factor k_d

Slots Per Pole Per Phase	No. of Phases		
s	3	2	1
1	1.000	1.000	1.000
2	0.966	0.924	0.707
3	0.960	0.911	0.667
4	0.958	0.906	0.653
5	0.957	0.904	0.647
6	0.956	0.903	0.644
7		0.902	0.642
8		0.902	0.641
9			0.940
10			0.639
∞	0.955	0.900	0.637

These values apply for all lap windings and wave windings; in the case of chain windings they apply when all slots contain an equal number of turns.

whose angle is less than 180 degrees with respect to the starting point, will not coincide with the 180-degree line. This can be proved by the fact that s is not an integer

$$\alpha = 180\frac{P}{N}$$

or

$$\frac{180}{\alpha} = \frac{N}{P} = \frac{a}{b} = m$$

which by previous definition is a fraction reduced to its lowest terms (a and b having no common factors).

By referring to Figure 4, it is shown that each of the m phases covers an mth part of the first 180 degrees and again of the next 180 degrees or half-cycle. Since the second half-cycle is negative relative to the first, the vectors in the second half-cycle must be reversed, before they can be *added* vectorially to those in the first part. In Figure 5, three vectors are shown which are to be added. Since vector 3 lies within the second half-cycle, it must be reversed as shown by vector 3′; the addition can then be carried out in the usual way.

For this reason it is now possible to enter, in the third column of the tabulation, new angular values, obtained by subtracting from the values in the second column that multiple of 180 degrees which will leave a positive remainder with a numerical value below 180 degrees, so that all vectors will lie between 0 and 180 degrees. In the fourth vertical column, the phases will be shown to which the coils in the slots in column 1 belong. To do this, the angle of each phase is determined as covering $180/m$ degrees, and the slots whose angles lie between 0 and $180/m$ degrees (exclusive), between $180/m$ and $(2\times180)/m$ (exclusive), between $(2\times180)/m$ and $(3\times180)/m$ (exclusive), and so forth, will belong to the various phases. The last column will then summarize the succession of the numbers of slots belonging to the different phases in their sequence around the armature, by counting the number of times a phase is repeated before being succeeded by the next phase. A check can be made by adding the number of slots in each phase, which must be equal to a.

One point has not been mentioned before, because it does not affect the result, except when it comes to making up a winding diagram or a connection diagram. It concerns the rotation of the phases and is shown in Figure 4. In a three-phase system the starts of the phases are 360/3 degrees = 120 degrees apart. Each covers 120 degrees, divided into two halves, one part covering 60 degrees in one direction and the other 60 degrees (180 degrees later) in the opposite direction. The actual phase sequence of the coils is therefore:

$+a$	$-c$	$+b$	$-a$	$+c$	$-b$
0°–60°	60°–120°	120°–180°	180°–240°	240°–300°	300°–360°

This phase sequence must be taken into account when the phases are assigned in the last column of the tabulation.

It is now possible to consider what happens to the distribution factor in this case. It is again necessary, according to the basic definition, to add the vectors of each phase both vectorially and also arithmetically. In order to add them vectorially, we must first determine the angle between them, and prove that this angle will be the same between all vectors.

It was previously determined that a section of $N/c = ma$ coils is repeated c times and covers $P/c = b$ poles. Consequently, the first vector of the second section must coincide with the first vector of the first section; since all vectors are considered to lie between 0 and 180 degrees (the others being reversed), it is necessary to determine how many times this 180 degrees is traversed before two vectors will coincide. This is given immediately by the fact that the repeated section covers b poles or $b\times180$ degrees, since each pole covers 180 degrees. The ma vectors per repeated section, which are α degrees apart, have a total angle of $ma\times\alpha$ degrees, which is equal to $b\times180$ degrees. However, all these vectors lie between 0 and 180 degrees. The first 180 degrees, the vectors are equally spaced α degrees apart. The next 180 degrees they will lie between those of the first 180 degrees. The next 180 degrees, they will again lie between those of the first and second section and so on, until after b times the vector will coincide with those previously present. Since the interval between vectors successively drawn is always equal to the angle between slots, the overlap will always be the same, and the successive vectors within the 180 degrees will be $\alpha_1 = 180/ma = \alpha/b$ degrees apart. Therefore, there will be a vectors per phase, α_1 degrees apart.

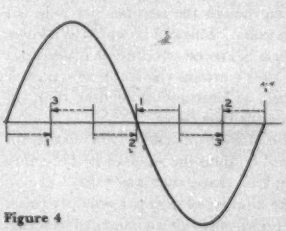

Figure 4

Another way of arriving at the same result is by considering that all vectors for the same phase lie evenly

distributed within an angle of $180/m$ degrees. Because there are a slots per phase in each section, the angle will be

$$\alpha_1 = \frac{\frac{180}{m}}{a} = \frac{180}{ma}$$

To explain this more clearly, suppose that the minute hand on a watch is advanced by intervals of 18 minutes starting at 12 o'clock, and that the positions at which the hand stops are marked on the face. The fourth time the hand will stop at 72 minutes or $72-60=12$ minutes. The seventh time it will stop at 126, or six minutes, and the tenth time it will stop again at 12 o'clock. The hour hand will have moved from 12 to 3. What we actually did was to find the least common multiple of 60 and 18, which is 180. The angle between points marking the stops is then found by finding the smallest fraction of 60 and 18, namely $60/18=10/3$. The angle between successive marks on the face will then be $60/10$ or $18/3=6$ minutes.

Similarly, we find the least common multiple of 180 degrees and α degrees. Since $\alpha=180b/ma$, where b/ma is irreducible, the least common mutiple will be $180\times b$. The angle between vectors will therefore be:

$$\alpha_1 = \frac{\alpha}{b} \text{ or } \alpha_1 = \frac{180}{ma}$$

Adding these a vectors vectorially gives

$$2R \sin \frac{a\alpha_1}{2}$$

and adding them arithmetically gives

$$2Ra \sin \frac{\alpha_1}{2}$$

The distribution factor is therefore

$$k_{d1} = \frac{2R \sin a\frac{\alpha_1}{2}}{2Ra \sin \frac{\alpha_1}{2}} = \frac{\sin a\frac{\alpha_1}{2}}{a \sin \frac{\alpha_1}{2}}$$

Since $\alpha_1 = \frac{180}{ma}$, we have

$$\sin a\frac{\alpha_1}{2} = \sin a\frac{\frac{180}{ma}}{2} = \sin \frac{180}{2m} = \sin \frac{90}{m}$$

and

$$a \sin \frac{\alpha_1}{2} = a \sin \frac{90}{ma}$$

Therefore

$$k_{d1} = \frac{\sin \frac{90}{m}}{a \sin \frac{90}{ma}}$$

For an integral number of slots per pole per phase, the distribution factor was found to be

$$k_d = \frac{\sin s\frac{\alpha}{2}}{s \sin \frac{\alpha}{2}}$$

$\alpha = 180\frac{N}{P}$ and $\frac{P}{N} = sm$, therefore $\alpha = \frac{180}{sm}$ and

$$k_d = \frac{\sin s\frac{180}{2sm}}{s \sin \frac{180}{2sm}} = \frac{\sin \frac{90}{m}}{s \sin \frac{90}{sm}}$$

By comparing k_d and k_{d1}, it is now seen that the two formulas agree in form.

To find the correct distribution factor in the case of a fractional number of slots per pole per phase, it is therefore necessary only to substitute a for s in the formula for the distribution factor for a whole number of slots per pole per phase. And a can be determined readily by writing the slots per pole per phase as an improper fraction. It is the numerator of that fraction. The denominator of the fraction does not appear in the result and is therefore immaterial as far as determining the effects of such a winding is concerned.

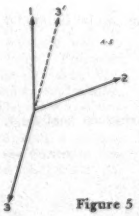

Figure 5

It is therefore possible to use the same table (Table I) for the distribution factor, regardless of whether the number of slots per pole per phase in an integer or a fraction. Interpolation is unnecessary and incorrect.

CONCLUSION

The electrical results of the use of a fractional number of slots per pole per phase are therefore the same as would have resulted from a larger number of slots, which would have given a whole number of slots per pole

Table II

Slot Number	Angle	Equivalent Angle	Phase	Grouping
1	0	0	a	
2	50	50	a	2
3	100	100	c	1
4	150	150	b	1
5	200	20	a	1
6	250	70	c	1
7	300	120	b	
8	350	170	b	2
9	400	40	a	1
10	450	90	c	1
11	500	140	b	1
12	550	10	a	1
13	600	60	c	
14	650	110	c	2
15	700	160	b	1
16	750	30	a	1
17	800	80	c	1
18	850	130	b	1

per phase equal to the numerator of the improper fraction expressing the slots per pole per phase, reduced to the smallest terms.

The design engineer should throw away his curve or interpolations and use the correct values from Table I. It will be less trouble to use the right value than the erroneous one previously used.

An example will be given to illustrate the method and to show the magnitude of the error.

EXAMPLE (SEE TABLE II)

The coil grouping and the distribution factor are to be determined for the following machine, having $P=20$ poles, $m=3$ phases and $N=72$ slots.

First it must be determined whether this combination can give a balanced winding, as follows

$$\frac{N}{P}=\frac{72}{20}=\frac{72/4}{20/4}=\frac{18}{5}$$

Since 18 is divisible by 3, the winding can be balanced. s will then be

$$s=\frac{N}{mP}=\frac{72}{3\times 20}=\frac{6}{5}=\frac{a}{b} \quad \text{and}$$

$a=6$, $b=5$, and $c=4$ (1, 2, and 4 parallel circuits are possible)

$$\alpha=\frac{180P}{N}=50°$$

$$\alpha_1=\frac{\alpha}{b}=\frac{50}{5}=10°$$

It is now possible to enter the proper values in the first three columns of Table II. In order to assign the three phases a, b, and c to the various slots and fill in column 4, it is necessary to consider the phase rotation as in Figure 4. It is then found that phase a is assigned to angles between 0 degrees and 180/3=60 degrees (exclusive), phase b to angles between (2×180)/3=120 degrees and (3×180)/3=180 degrees (exclusive) and phase c to angles between 180/3=60 degrees and (2×180)/3=120 degrees (exclusive). When the fourth column has been completed, the coils are grouped as in column 5.

The angles for the vectors of phase a will then be 0°–50°–20°–40–10°–30°, or 6 vectors, 10 degrees apart.

The distribution factor will be

$$k_{d1}=\frac{\sin\frac{90}{m}}{a\sin\frac{90}{ma}}=\frac{\sin 30}{6\sin\frac{90}{18}}=0.956$$

From the table, for $s=6$ and 3 phases. $k_d=0.956$.

The value taken from a curve would be 0.982; by interpolation it would be 0.993.

The error in the first case would be 2.72 per cent, and in the second case 3.87 per cent.

The error in the reactance value would be 5.5 per cent in the first case and 7.9 per cent in the second case, since the distribution factor occurs to the second power in the equation for that value.

The errors can, of course, become still larger for two-phase and for single-phase machines.

General Electric Photo

This transformer, being installed on the Brooklyn (N. Y.) Edison system, has a rating of 75,000 kva, 60 cycles, and 132,000 volts, with two separate low-voltage windings, each for 13,500/27,000 volts. The equivalent two-winding rating is 84,000 kva. Provision is made for addition of forced-air cooling whereby the rating can be raised to 150,000 kva

INSTITUTE ACTIVITIES

North Eastern District Technical Meeting to Be Held April 8–9

A technical meeting of the AIEE North Eastern District will be held on April 8 and 9, 1943, at Pittsfield, Mass., with headquarters at the Wendell Hotel. Subjects of importance to electrical engineers in fulfilling their professional duties in war time will be stressed at the meeting.

Five technical sessions on the tentative program are planned to cover the following subjects:

Electronics, a field that is being greatly stimulated by the war.

Power transmission and distribution, and industrial control and power applications, two subjects of primary importance as industry strives to achieve maximum output.

Measurements and instrument transformers, new developments in the field.

Plastics, which are playing an important part in the war effort.

Technical papers will be presented in all five of these categories.

It is planned also to hold three conferences to facilitate the free exchange of ideas on problems of present-day importance to engineers. These include a clinic for industrial operators of electrical equipment at which methods of getting the most from available apparatus will be discussed; ways in which the engineering profession can make the greatest contribution to the community will be the subject of a conference on engineering councils; and the place of the engineer in the war effort will be discussed at another conference on the wartime problems of technical personnel.

Since AIEE members must keep abreast of technological developments important to the war effort, with the minimum expenditure of time, a full technical program is being presented in two days, rather than in three days as in past years, by retaining in the program only those elements that are essential under present circumstances.

National Technical Meeting Report to Appear in March Issue

As this issue of *Electrical Engineering* goes to press the 1943 AIEE national technical meeting is in progress in New York, N. Y. Indications are that this meeting, keyed to many phases of the war activity, will be equally as successful as others held in recent years, despite war conditions. Registration for the first two days is reported to be 1,115 as compared with 1,059 for the first two days of 1942 meeting, 1,278 for 1941, 1,178 for 1940, and 1,159 for 1939.

A full report of the meeting will be published in the March issue.

Future AIEE Meetings

District Technical Meeting
Pittsfield, Mass., April 8–9, 1943

District Technical Meeting
Kansas City, Mo., April 28–30, 1943

National Technical Meeting
Cleveland, Ohio, June 21–25, 1943

No Fortescue Fellowship Award to Be Made for 1943–44

Because of conditions brought about by the war, there will be no meeting of the Fortescue Fellowship committee and no award of the Charles Legeyt Fortescue Fellowship, which annually provides graduate fellowships in electrical engineering, for the year 1943–44. The funds available are to be impounded. Suspension of the award is in accordance with a motion passed at a meeting of the Fortescue Fellowship committee held on March 25, 1942.

AIEE Advertising Manager, C. A. Graef, Dies

Charles A. Graef, AIEE advertising manager for the past 20 years, died January 20, 1943 at his home in Brooklyn, N. Y., at the age of 53. He had been ill for several months.

Mr. Graef was born in New York, N. Y., and was educated in public and high schools in Brooklyn. During World War I he served overseas, and after the armistice was an official stenographer in Paris, France, for the Peace Commission. He became associated with the AIEE in 1911, and had been advertising manager since 1923.

PERSONAL • • • •

G. W. Dunlap (A '35, M '42) development engineer in the laboratories of the General Electric Company, Schenectady, N. Y. has been awarded the Alfred Noble prize for 1942 for his paper, "The Recovery Voltage Analyzer for Determining of Circuit Recovery Characteristics" (AIEE *Transactions*, volume 60, 1941, November section, pages 958–62). He was born on April 13, 1911, in Gardnersville, Nev., and received from Stanford University the degree of bachelor of arts in 1931, that of engineer in electrical engineering in 1933, and that of doctor of philosopy in 1936. From 1932 to 1935 he held the Harris J. Ryan High-Voltage Research Laboratory Fellowship. In 1935 he entered the testing department of the General Electric Company in Schenectady and was transferred in 1936 to the high-voltage and impulse section of the general engineering labora-

G. W. Dunlap

tory. There he is responsible for the development and application of devices concerned with measurements in the field of high-voltage and high-speed transients. In 1933 he won the AIEE San Francisco Section prize for the best student paper. He is also a member of Sigma Xi and Tau Beta Pi.

D. C. Jackling (M '41) managing director, mining operations, Kennecott Copper Corporation, San Francisco, Calif., has retired. He will continue as a director of that company. Mr. Jackling was born on August 14, 1869, at Hudson, Mo., and received from the Missouri School of Mines and Metallurgy the degrees of bachelor of science in 1892, metallurgical engineer in 1900, and doctor of engineering in 1933. He holds the honorary degrees of doctor of laws from the University of California, and doctor of engineering from the University of Southern California. He began his career as a rodman and instrument man on the Missouri, Kansas, and Texas Railroad in 1890 and 1891. For the following two years he was assistant professor of chemistry and metallurgy at the Missouri School of Mines and Metallurgy, Rolla. Then came two years with the Lawrence Gold Extraction Company, Colo., as miner, assayer, metallurgist, and mill superintendent. In 1896 he built and operated an experimental mill at Mercur, Utah. From 1897 to 1900 he was engaged in building and operating, at Mercur, a gold mill, which was one of the first to be built entirely of steel and concrete and to be driven exclusively by electric power, using 3-phase alternating current. From 1900 to

1922 he developed mine properties, and designed and constructed plants for treating their ores, in Utah, Nevada, Arizona, Alaska, Colorado, Montana, and New Mexico. The mines involved included those of the United States Reduction and Refining Company, the Butts and Superior Mining Company, the Alaska Gold Mines, the Mesabi Iron Company, the Gallup American Coal Company, the Utah Copper Company, the Ray Consolidated Copper Company, the Chino Copper Company, and the Nevada Consolidated Copper Company. He was most closely associated with the last six companies, of which he became president. Studies made in his early days at Mercur on the possibilities of commercializing low-grade ores led to the establishing of the Utah Copper Company. Since 1922 he has been engaged in executive work in the mining industry. He received the United States Distinguished Service Medal in 1919, the gold medal of the Mining and Metallurgical Society of America in 1926, the William Lawrence Saunders Gold Medal of the American Institute of Mining and Metallurgical Engineers in 1930, the John Fritz Medal of the Engineering Societies of New York in 1933, and the Washington Award in 1940.

William Wilson (M '23) assistant vice-president of Bell Laboratories, Inc., New York, N. Y., has retired. He was born March 29, 1887, at Preston, England, and was educated at the Universities of Manchester and Cambridge. He received the degrees of bachelor of science, master of science, and doctor of science from the former and the degree of bachelor of arts from the latter. Mr. Wilson's retirement terminates a 28-year association with the Bell Telephone system. His first position with the company, in 1914, was that of an observer on transcontinental wireless telephone tests at the San Diego, Calif., station. From 1914 to 1923 he was charged with development and research work on vacuum tubes in the research department of the Western Electric Company, Inc., New York, N. Y. During 1918 he supervised the manufacture of power tubes for that company. He held the position of assistant director of research of the Bell Laboratories from 1927 to 1936. As such, he organized research on problems of wire and radio communication. Since 1936 he had been assistant vice-president in charge of personal relations. Before joining the Western Electric company, Mr. Wilson lectured on physics at the University of Toronto for two years. He holds patents on vacuum tubes and is the author of articles in English and German on radioactivity, thermionics, vacuum tubes, and radio. He is a fellow of the American Physical Society, and a member of the Institute of Radio Engineers.

R. F. Pack (A '11, M '12) president of the Northern States Power Company, Minneapolis, Minn., has retired from the presidency of the company to become chairman of the board. He was born on October 1, 1874, on the Isle of Wight. He was employed by the Toronto Electric Company in 1891 and became successively accountant, comptroller, secretary, and general manager. In 1912 he became associated with the Byllesby Engineering and Management Corporation, Chicago, Ill., as general manager of the Minneapolis General Electric Company, Minn. (now a division of the Northern States Power Company). He was appointed general manager of the Northern States Power Company in 1916 and shortly afterwards, vice-president, and later, president. In 1936 he was elected to the board of directors of the Byllesby company. He will continue as president of the Northern States Power Company of Delaware.

S. C. Medbery (A '02, M '30) engineer of maintenance practices for the New York (N. Y.) Telephone Company, retired on January 1, 1943. He was born on September 7, 1878, at Ballston Spa, N. Y., and graduated from Union College with the degree of bachelor of science in electrical engineering. His engineering career began in the testing department of the General Electric Company in 1899. From 1901 to 1904 he was electrician in charge of central stations for the Virginia Passenger and Power Company, Richmond. In 1905 he joined the New York and New Jersey Telephone Company doing tests and inspections. In 1907 he joined the engineering department of the New York Telephone Company, where he worked on inductive co-ordination, transmission, electrolysis, and equipment maintenance practices. In 1925 he was made engineer of maintenance practices.

J. I. Hull (M '16) assistant to the manager of the River Works of the General Electric Company, West Lynn, Mass., has been appointed to full-time service as engineer in charge of the Thomson Laboratory of the River Works. Since 1937 Mr. Hull has held the two positions of assistant to the manager on engineering activities and engineer in the Thomson Laboratory. He received his bachelor of philosophy degree from Yale University in 1908 and his bachelor of arts degree from that university in 1909. He began his career in the testing department of the General Electric company's works in Pittsfield, Mass. In 1910 he was transferred to the General Electric company in Schenectady, N. Y., where he was designing engineer in the induction motor department until 1930. In 1931 he became assistant to the manager of the West Lynn River Works.

D. L. Beeman (A '31) industrial engineering department, General Electric Company, Schenectady, N. Y., has recently been appointed engineer, industrial power section. He received the degree of bachelor of arts in electrical engineering from Stanford University in 1929, and immediately entered the employ of the General Electric Company in the test course as student engineer. He was engaged subsequently on test work at that company's plants in Pittsfield, Mass., and Philadelphia, Pa., and later was transferred to the relay-engineering division of the switchgear department in Philadelphia. In 1935 he joined the air-circuit-breaker engineering division there, and in 1936 he was transferred to the central-station engineering department at Schenectady, N. Y. He has been an application engineer in the industrial power section since 1941.

A. F. Connery (A '23) inside engineer, plant and engineering department, has been appointed chief engineer. He was employed (1917–20) with the Great Northwestern Telegraph Company, at Winnipeg, Man., Saskatoon, Sask., and Montreal, Que. and the Western Union Telegraph Company, New York, N. Y. (1920–22). He first joined Postal Telegraph-Cable Company in 1922, serving until 1928 as inside plant engineer. Subsequently he served in a similar capacity for International Telephone and Telegraph Company, International Communications Laboratories, and the All America Cable Company. He rejoined the Postal Telegraph Company in 1939 as equipment engineer, and has been associated with that company continuously since that time.

W. N. Lindblad (A '37, M '41) assistant chief, bureau of test and inspection, Pacific Gas and Electric Company, Emeryville, Calif., recently has been appointed chief of the test and inspection bureau. He has been associated with Pacific Gas and Electric Company continuously since 1913, except for a brief period during World War I when he served from 1918 to 1919 in the United States Army Air Service. From 1913 to 1914 he was employed as a meter tester, and since then has served successively as laboratory assistant (1914–17), assistant superintendent of the electrical laboratory (1917–19), and assistant chief to date. He was graduated from Polytechnic College of Engineering in 1913.

J. O. Walz (A '21, M '42) manager of engineering, small motor engineering department, Westinghouse Electric and Manufacturing Company, Lima, Ohio, has recently been appointed assistant manager of the division. He was transferred to the Lima works from the Westinghouse student course in East Pittsburgh, Pa., in which he was enrolled from 1918 to 1919. He has been associated with the small motor engineering department since 1919, serving successively as design engineer, section engineer, and ultimately as manager of engineering.

W. R. MacDonald, Jr. (A '33) formerly captain in the Signal Corps, United States Army, with headquarters at Washington, D. C., has recently been appointed a major. He is now head, editing subsection, literature section, military training branch, Office of Chief Signal Officer, Washington, D. C. He has been with this office since his commission in 1941 as first lieutenant. He is now on wartime leave of absence as

assistant editor for the American Institute of Electrical Engineers, where he has been employed in the editorial department since 1934.

J. O. Johnson (A '36) chief product engineer of the Aircraft-Marine Products, Inc., Elizabeth, N. J., has been made assistant merchandise manager of that company. From 1931 to 1934 he was employed by Sears, Roebuck and Company, first in the office of the technical director and later in the merchandise development division. He worked as junior material engineer and assistant material engineer in the laboratory of the Brooklyn Navy Yard from 1934 to 1940, when he joined the Aircraft-Marine company.

H. W. DeWitt (M '40) engineer, maintenance and related matters, New York (N. Y.) Telephone Company, has been transferred from the Manhattan-Bronx-Westchester area to the operations and engineering department, to work in the appraisal practices group of the operating results division. Mr. DeWitt has been with the New York Telephone Company since he graduated from Stevens Institute of Technology with the degree of mechanical engineer in 1927.

G. Ross Henninger (A '22, M '27) AIEE editor on leave, has been assigned to the Air Service Command at Patterson Field, Fairfield, Ohio. Lieutenant Colonel Henninger is now chief of the Reproduction Branch of the Technical Data Section, which is charged with assembling technical data for the United States Air Forces throughout the world. He was formerly liaison officer on the headquarters staff of the Army Specialist Corps in Washington, D. C.

R. R. Donaldson (M '17) vice-president of the Utility Management Corporation, New York, N. Y., has been made head of a department to render advisory and supervisory services to operating utilities for Gibbs and Hill, Inc., New York, N. Y. Mr. Donaldson received the degree of mechanical engineer from Cornell University in 1907. He joined the Utility Management Corporation in 1926 as assistant chief engineer.

G. W. Swenson (A '19, F '36) professor of electrical engineering and head of the department, Michigan College of Mining and Technology, Houghton, has been granted leave of absence to accept a position as special consultant with the United States Army Air Force, Orlando, Fla. **Chester Russell, Jr.** (A '29, M '34) associate professor of electrical engineering at the college, has been appointed acting head of the department in his absence.

Thomas Ingledow (M '41) chief engineer, British Columbia Electric Railway Company, Ltd., has been elected chairman of the AIEE Vancouver Section for 1942–43. Other officers include **T. F. Hadwin** (A '35) assistant superintendent, construction and maintenance, British Columbia Electric Railway Company, Ltd., vice-chairman; and **F. V. Knight** (A '25) substation operator, British Columbia Electric Railway Company, Ltd., as secretary.

L. O. B. Lindstrom (A '22) sales representative, General Electric Company, San Francisco, Calif., has become a partner in the A. E. Smith Engineering Company, San Francisco, Calif. He had been associated with General Electric Company since 1920. Prior to that time he worked briefly as operator (1919–20) with the Utah Power and Light Company, and as electrician on construction (1920) for the Southern California Edison Company.

David Williams (A '23) manager, electrical and mechanical equipment purchases, purchasing and stores department, Consolidated Edison Company of New York (N. Y.), Inc., has been appointed lieutenant commander, United States Naval Reserves, and is now on duty as head of the engineering section, commodities branch, purchase division, Bureau of Supplies and Accounts, Washington, D. C.

J. E. Piccardo (A '36) chief engineer, Jacuzzi Brothers, Inc., Berkeley, Calif., has been appointed mechanical engineer in production, San Francisco Ordnance district, United States War Department. He has been associated with Jacuzzi Brothers, Inc., since his graduation from the University of California with the degree of bachelor of science in electrical engineering in 1935.

H. V. Schofield (A '40) equipment engineer, Illinois Bell Telephone Company, Chicago, has been transferred to the operations and engineering department of the New York (N. Y.) Telephone Company where he will take charge of the group handling engineering matters relating to central office and private-branch-exchange equipment. He has been with the Illinois company since 1927.

C. F. Scott (A '92, F '25, HM '29) professor of electrical engineering emeritus, Yale University, New Haven, Conn., has been appointed a member of the sectional committee on definitions of electrical terms of the American Standards Association. Doctor Scott is a past president (1902–03) and past vice-president (1899–1901) of the Institute. He received the Edison Medal in 1929.

J. C. Michalowicz (A '41) assistant research engineer, technical standards department, Rural Electrification Administration, Washington, D. C., has been appointed instructor in the department of electrical engineering, The Catholic University of America, Washington, D. C. He received the degree of bachelor of electrical engineering from that institution in 1940.

Gregory Timoshenko (A '33, M '39) assistant professor of electrical engineering, University of Connecticut, Storrs, has recently been appointed associate professor. Before joining the teaching staff of the engineering department at that institution he served as instructor in electrical engineering (1934–39) at Massachusetts Institute of Technology.

R. B. Shepard (A '25, F '36) deputy chief of the simplification branch of the bureau of industrial conservation of the War Production Board, Washington, D. C., has been appointed chief of the simplification branch. At the time of his appointment to the WPB he was chief electrical engineer, Underwriters Laboratories, Inc., New York, N. Y.

E. B. Whitman (M '34) partner, Whitman, Requardt, and Smith, Baltimore, Md., consulting engineers, has been elected president of the American Society of Civil Engineers. He was graduated from Cornell University in 1901 with the degree of chemical engineer, and has served as a past director of the society.

F. R. Lack (M '37) vice-president and manager, radio division, Western Electric Company, New York, N. Y., is on leave of absence serving as director of the Army–Navy Electronics Expediting Agency. He will supervise all Army and Navy joint activities expediting production of communications and radio equipment.

W. J. Russell (M '37) manager of engineering, Westinghouse Electric and Manufacturing Company, Mansfield, Ohio, has been awarded the Westinghouse Order of Merit, "in recognition of distinguished service in the field of engineering." He has been with the Westinghouse company since 1923.

Ellis Blade (A '35) consulting engineer, and formerly chief engineer of the spring division, John Chatillon and Sons, New York, N. Y., has recently been appointed a wire and cable specialist for the United States Army Signal Corps, with headquarters in Washington, D. C.

D. L. Smith (M '27) engineering assistant to the executive officer, Chicago (Ill.) Rapid Transit Company, has been ordered to active duty with the United States Army Field Artillery Reserves, as lieutenant colonel. He is stationed in San Francisco, Calif.

James J. Pilliod (M '17, F '34) general manager of the long-lines department of the American Telephone and Telegraph Company, New York, N. Y., has been given a leave of absence to join the production division, Services of Supply of the War Department, Washington, D. C.

F. M. Farmer (A '02, F '13) vice-president and chief engineer of the Electrical Testing

Laboratories, New York, N. Y., has been elected vice-president of the United Engineering Trustees. He is a past president (1939–40) of the Institute.

J. R. Shoffner (A '29, M '37) chief engineer of the Allegheny River Mining Company, Kittanning, Pa., since 1936 has been elected state director, representing Pittsburgh, on the executive board of the Pennsylvania Society of Professional Engineers.

William Biester (A '41) president of the Electric Construction Company, Philadelphia, Pa., has been appointed an alternate member of the American Standards Association's sectional committee on the national electrical code.

Leonard T. Blaisdell (A '20, F '39) commercial vice-president of the General Electric Company, Cleveland, Ohio, has received the honorary degree of electrical engineer from the Case School of Applied Science.

A. R. Williams (M '31, F '35) lieutenant colonel, United States Army, formerly with the power branch of the War Production Board has been made chief of the power section of the Army and Navy Munitions Board.

O. E. Buckley (M '19, F '29) president of the Bell Telephone Laboratories, Inc., New York, N. Y., has been appointed by the War Production Board to a committee which will set up the proposed Office of Technical Development within the WPB.

L. W. Chubb (A '09, F '21) director of research, research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed to the research procedure committee of the Engineering Foundation.

Lysle W. Morton (A '38) electrical engineer with the General Electric Company, Schenectady, N. Y., has been appointed a member of the subcommittee on mercury-arc rectifiers of the American Standards Association.

Willard Champe (A '25, M '35) electrical engineer for the city of Toledo, Ohio, has been elected chairman of the AIEE Toledo Section. Mr. Champe was assistant editor of *Electrical Engineering* from 1931 to 1936.

E. H. Colpitts (A '11, F '12) retired vice-president of the Bell Telephone Laboratories, New York, N. Y., has been re-elected director of the Engineering Foundation.

J. S. Murray (A '21, M '31) chief electrical engineer for the Follansbee Steel Corporation, W. Va., has been elected national treasurer of the Association of Iron and Steel Engineers.

H. F. Dart (A '20, M '26) electronics tube engineering department, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J., has been elected secretary of the Institute of Radio Engineers.

OBITUARY • • • •

William Slocum Barstow (A '94, F '12) retired president of Barstow, Tyng and Company, New York, N. Y., died on December 26, 1942. He was born on February 15, 1866 in Brooklyn, N. Y., and graduated from Columbia University with the degree of bachelor of arts in 1887. In 1935 he received an honorary degree of doctor of science from that university. He also possessed an honorary degree of doctor of engineering from Stevens Institute. He was employed by the Edison Machine Works in Schenectady, N. Y., Paterson, N. J., and New York, N. Y., from 1890 to 1897, when he joined the Edison Electric Illuminating Company in Brooklyn as assistant superintendent. He served as general superintendent and chief engineer of that company from 1890 to 1897 when he became general manager. In 1901 he left the Edison company to become an independent consulting engineer. In 1906 he established the firm, W. S. Barstow and Company, Inc., and became its first president. He organized the General Gas and Electric Corporation in 1912 and served as president until 1929. In that year he became president of Barstow, Tyng and Company. For many years he was officer of the Association of Edison Illuminating Companies, serving as secretary, treasurer, and a member of the executive committee. He was the author of a number of technical papers and held patents on such devices as a two-rate meter, clock switches, and a booster for storage batteries. He was a member of the United States Government Committe on the Super-Power System for the Eastern States and the jury of awards of the Pan-American Exposition at Buffalo, N. Y. From 1903 to 1905 he was vice-president of AIEE and a manager from 1900 to 1903. His other society affiliations included: founder and honorary president of the Edison Pioneers, trustee of Stevens Institute, president of the Thomas Alva Edison Foundation, member of the American Electro-Chemists Society, the Electrical Society, and the Illuminating Engineering Society. In addition he held the office of mayor of Kings Point village, Great Neck, N. Y., from 1924 to 1937. He was responsible for the erection of the Edison Tower at Menlo Park, N. J. (*EE, Nov. '42, p. 581*).

Nikola Tesla (A '88, F '17) electrical inventor, died on January 7, 1943. He was born in 1857 in Smitjan, Lika, Yugoslavia. He studied mathematics and physics at the Polytechnic School at Gratz, and philosophy at the University of Prague. In 1894 he received the honorary degrees of master of arts from Yale University and doctor of laws from Columbia University. He also held a degree of doctor of science from the Vienna Polytechnic Institute. Mr. Tesla began his career with the invention of a telephone repeater in 1881 in Budapest, Hungary. Later he did engineering work in Germany and France, coming in 1884 to the United States, of which he became a naturalized citizen. For a time he worked with Thomas A. Edison, chiefly designing motors and generators. Then he joined the Westinghouse company. In 1888 came his invention of the system of a-c power transmission which revolutionized industrial power transmission. Most of his other inventions, for which he held numerous patents, were made before 1900. He invented, in 1886, a system of arc lighting; in 1889, a system of electrical conversion and distribution by oscillatory discharges; in 1890, a generator of high-frequency currents; in 1891, a system of transmitting energy over a single wire without return, and the Tesla coil; in 1893, a system of wireless transmission; in 1894, a mechanical oscillator and generator of electrical oscillations; in 1897 a system of transmitting energy without wires, and a high-potential magnifying transmitter. Of late years he had been concerned principally with the possibilities of transmitting power without wires, particularly to ships at sea. AIEE presented the Edison medal to him in 1916 for "early original work in polyphase and high-frequency electric currents." For his contributions to science and engineering he was awarded the Order of the White Lion by Czechoslovakia. He served as AIEE vice-president from 1892 to 1894. He was also the recipient, in 1893, of the Elliott G. Cresson gold medal for original work presented before the Franklin Institute.

Carl G. Koppitz (M '21) vice-president and consulting engineer of the Railway and Industrial Engineering Company, Greensburg, Pa., died on January 6, 1943. Mr. Koppitz was born on January 10, 1878, at San Francisco, Calif. He began his career in 1896 as a powerhouse operator for the Electric Improvement Company, San Jose, Calif., and during 1898–99 worked as a lineman and foreman for the Phoenix Power Company, Tuolumnie County, Calif. In 1900 he worked in France on the construction and operation of the Westinghouse exhibit in the Paris exposition. While in Paris he also had charge of the operation and construction of the Vitry and Bazon powerhouses of the Cie des Tramways de 1 Est Parisien and supervision of their substations. In 1902 and 1903 he was sales engineer for the Westinghouse Electric and Manufacturing Company in London and Birmingham, England. He was engaged in consulting engineering work as a partner in the firm, Sprout and Koppitz, San Francisco, Calif., during 1904. He worked as electrical engineer for the Youngstown Consolidated Gas and Electric Company and the Mahoning and Shenango Railway and Light Company from 1908 through 1911. Following a period of research in 1912, he was employed as a designer of powerhouses for the West Penn Power Company. He joined the Railway and Industrial Engineering Company in 1914 and was for many years chief engineer of that company. He was a member of the American Chemical Society and the American Association for the Advancement of Science.

Edwin Jay Prindle (A '06, M '20) retired patent attorney, died on December 17, 1942. He was born in Washington, D. C., on November 5, 1868, and received the degree of mechanical engineer from Lehigh University in 1890. He received from National University (later George Washington University) the degrees of bachelor of laws in 1902, and master of laws in 1904. He received the honorary degree of doctor of laws from that university in 1930 and that of doctor of engineering from Lehigh University in 1934. From 1890 to 1899 he worked as assistant examiner in the United States Patent Office. He practiced patent law in Washington until 1905, when he went to New York to carry on similar work involving electrical inventions. He was for some time senior partner in the patent law firm of Prindle, Bean, and Mann. He played a prominent part in educating the public to the value of the United States patent system and in securing reforms in the patent law. Author of a number of papers on patent law, he held several patents on inventions of his own. He was a past president of the New York Patent Law Association, and also served as chairman of the patent committees of the National Research Council and the National Association of Manufacturers. In addition he was a member of the American Society of Mechanical Engineers, American Institute of Mining and Metallurgical Engineers, American Chemical Society, American Electrochemical Society, and Tau Beta Pi.

Robert Michael Spurck (A '18, F '37) manager of sales, circuit breaker section, switchgear division, central station department, General Electric Company, Philadelphia, Pa., died on December 12, 1942. He was born at Nelson, Nebr., on July 2, 1888. Graduating in 1910 from the University of Illinois with the degree of bachelor of science in electrical engineering, he joined the General Electric Company, Schenectady, N. Y. In 1913 he received the degree of master of science from Union College. After working in the testing department of the General Electric company from 1910 to 1912, he was transferred to the switchgear engineering department. In 1914 he was placed in charge of the design and application of oil circuit breakers. Appointed assistant engineer in the switchgear department in 1925, he supervised engineering, development, design, testing, and application of switchgear apparatus. He was transferred to the company's Philadelphia works in 1928 as assistant engineer in charge of all apparatus design and engineering. In 1931 he was made assistant engineer, assisting in supervision, engineering development, and application of all apparatus manufactured in the Philadelphia works. He became manager of sales in 1935.

Fred Irvin Woltz (A '10, M '34) of the E. A. Wilcox Company, San Francisco, Calif., died on November 27, 1942. He was born on March 4, 1883 in Washington, D. C., and in 1909 graduated from Pennsylvania State College with a degree of bachelor of science in electrical engineering. In 1913 he received the degree of electrical engineer from that college. From 1909 to 1913 he worked on transformer and motor design in the engineering department of the Wagner Electric and Manufacturing Company, St. Louis, Mo. He did transmission-line studies and operation and construction supervision from 1913 to 1916 for the Idaho Power and Light Company, Twin Falls. Until 1918 he was power engineer for the Union Gas and Electric Company, Cincinnati, Ohio. From 1918 to 1925 he was in charge of power sales for the Central Hudson Gas and Electric Company, Poughkeepsie, N. Y. He later joined the engineering staff of the General Engineering and Management Company, New York, N. Y., where he was operating and construction assistant to the supervisor of middle western properties. In 1928 he became manager of industrial power service at the Metropolitan Edison Company, Easton, Pa. He had been employed by the Wilcox Company for about four years.

Alfred E. Seelig (A '07) president and general manager of the L. J. Wing Manufacturing Company, New York, N. Y., died on September 13, 1942. He was born on September 6, 1887, at New York, N. Y., and graduated from Columbia University with the degree of electrical engineer in 1907. He immediately entered the employ of the Electro Bleaching Gas Company, New York, N. Y., to work on the development of a new bleaching gas. In 1910 he became New England representative for the Wing company and in 1911, sales manager. Following a period as general manager of the Atlantic Communication Company in 1912, he became sales manager of the Kerr Turbine Company in Wellsville, N. Y. In 1917 he returned to the Wing company as president and general manager. He was also a member of the American Society of Mechanical Engineers and the American Society of Heating and Ventilating Engineers.

Lathorp Burtt Abeel (A '31) superintendent of stations for the Buffalo Niagara Electric Corporation, North Tonawanda, N. Y., died on October 20, 1942. He was born on July 29, 1883. He worked as operator and engineer for the Hudson Valley Railway Company from 1901 to 1907, when he was charged with handling new business and contracts. He joined the Burlington Light and Power Company as operator and engineer in 1913, and in 1916 joined the Consumers Power Company as engineer. In 1918 he became an operator for the Tonawanda Power Company (later merged with two other companies to become Buffalo Niagara Electric Company) and in 1933 he was made chief operator in charge of substations.

Charles J. Goldmark (A '88) retired consulting engineer, died on November 3, 1942. He was born in Brooklyn, N. Y., in 1867. He was graduated from Yale University where he studied mechanical engineering in 1887. He then took a course in electrical engineering at Cornell University from which he graduated in 1889. He was employed in the testing department of the Sprague Electrical Railroad and Motor Company, New York, N. Y., during 1888. As a consulting engineer, he specialized in the design and construction of railroad shops in the United States and Canada.

Claude Stratton Noble (A '18, M '29) transmission superintendent with the Tampa (Fla.) Electric Company died September 17, 1942. He was born in Salem, Oreg., on September 2, 1885, and attended the college of engineering of the University of Washington. From 1907 to 1910 he was employed by the Puget Sound Traction, Light and Power Company, Seattle, Wash., as station operator, and in 1910 became load dispatcher. He served as suburban district supervisor for the Puget Sound Light and Power Company from 1920 to 1926, when he became valley division superintendent. In 1926 he joined the Tampa Electric Company.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meeting on January 21, 1943, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Hopkins, R. A., head electrical engineer, Tennessee Valley Authority, Knoxville, Tenn.

Kinnard, I. F., executive engineer, General Electric Company, West Lynn, Mass.

Penniman, A. L., general superintendent, electrical operations, Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Whitehurst, R., assistant general sales manager, The Electric Storage Battery Company, Philadelphia, Pa.

Wright, E. M., assistant engineer, Pacific Gas and Electric Company, San Francisco, Calif.

5 to grade of Fellow

To Grade of Member

Atwell, C. A., design engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Broadwell, E. D., assistant professor of electrical engineering, Rensselaer Polytechnic Institute, Troy, N. Y.

Carter, G. K., electrical engineer, General Electric Company, Schenectady, N. Y.

Goss, J. H., engineer in charge, General Electric Company, West Lynn, Mass.

Holmes, I. C., assistant professor of electrical engineering, Rensselaer Polytechnic Institute, Troy, N. Y.

Iden, R. D., distribution superintendent, The Ohio Public Service Company, Mansfield, Ohio.

Jewell, R. G., development engineer, General Electric Company, Lynn, Mass.

Krazel, F. J., assistant chief engineer, shops, E. I. du Pont de Nemours Company, Pryor, Okla.

May, M., senior engineer, War Department, Corps of Engineers, St. Louis, Mo.

McCune, F. K., design engineer, General Electric Company, West Lynn, Mass.

McLean, C. R., superintendent, Mountain States Power Company, Albany, Oreg.

Osburn, O. R., professor, State College of Washington, Pullman, Wash.

Pulaski, S. S., experimental test engineer, Perfex Corporation, Milwaukee, Wis.

Rice, P. X., associate professor, Pennsylvania State College, State College, Pa.

Sims, W. B., assistant department head, Ebasco Services, Inc., New York, N. Y.

Sofiano, G. C., electrical engineer, The Electric Construction Company, Ltd., Birmingham, England.

Stein, L. B., assistant electrical engineer, United States Navy Department, New York, N. Y.

Stratford, F. J., toll testing engineer, Western Electric Company, Inc., New York, N. Y.

Tudbury, C. A., experimental engineer, The Ohio Crankshaft Company, Cleveland, Ohio.

VanDeusen, E. J., electrical design engineer, Mason and Hanger Company, Baraboo, Wis.

Westerkamp, P. R., commercial engineer in charge, Consolidated Edison Company of New York, N. Y.

Wilson, M. S., design engineer, General Electric Company, Lynn, Mass.

Wisner, L., lieutenant commander, United States Naval Station, Manhattan Beach, Calif.

Yarmack, J. R., commercial engineer, Federal Telegraph and Radio Corporation, East Newark, N. J.

24 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before February 28, 1943, or April 30, 1943, if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Abbott, C. E., Signal Corps, Massachusetts Institute of Technology, Cambridge, Mass.

Albert, L. I., Colts Patent Firearms Manufacturing Company, Hartford, Conn.

Armstrong, I. W., Dinion Coil Company, Caledonia, N. Y.

Ayvasian, M. H. (Associate re-election), New England Power Service Company, Boston, Mass.

Bliss, P., New Britain Machine Company, New Britain, Conn.

Brockner, C. E., Union College, Schenectady, N. Y.

Buts, C. H., Sylvania Electric Products, Incorporated, Ipswich, Mass.

Chu, D. C., General Electric Company, Schenectady, N. Y.

Clarke, G. C., Jr., General Electric Company, Schenectady, N. Y.

Coullard, J. B., General Electric Company, Bridgeport, Conn.

Davis, R. V., General Electric Company, Pittsfield, Mass.

de Ferranti, M. A. (Member), Curtiss-Wright Corporation, Buffalo, N. Y.

DeLerno, M. J., General Electric Company, Schenectady, N. Y.

Dietze, T. W., General Electric Company, Lynn, Mass.

Dikmen, B. I., Manning, Maxwell and Moore, Bridgeport, Conn.

Dobbins, W. K. (Member), Seneca Vocational High School, Buffalo, N. Y.

Ellenburg, R. B., Radar School, Bowdoin College, Brunswick, Me.

Fleming, W. J., General Electric Company, Schenectady, N. Y.

Frisbie, G. W., 43 Arlington Street, Pittsfield, Mass.

Gaba, H. F., Signal Corps, U. S. Army, Electronics Training Center, Boston, Mass.

Gagne, J. W., General Electric Company, Schenectady, N. Y.

Greenleaf, F. D., South Street, Foxboro, Mass.

Harrell, R. F., Massachusetts Institute of Technology, Cambridge, Mass.

Hedlund, C. F. (Member), Associated Factory Mutual Fire Insurance Companies, Boston, Mass.

Hendricks, G. B., General Electric Company, Schenectady, N. Y.

Hertz, L. M., General Electric Company, Schenectady, N. Y.

Himes, B. T., Jr., U.S.N.R., Massachusetts Institute of Technology, Cambridge, Mass.

Jerrems, A. S., Massachusetts Institute of Technology, Radiation Laboratory, Cambridge, Mass.

Klug, K. W., United States Signal Corps, Austin Hall, Harvard University, Cambridge, Mass.

Kritscher, A. J., General Electric Company, Schenectady, N. Y.

Lodal, O. T. (Member), United States Engineer Office, Cooperstown, N. Y.

Lovewell, E. B. (Member), New Britain Machine Company, New Britain, Conn.

Massingill, J. A., General Electric Company, Schenectady, N. Y.

McEntire, K., General Electric Company, Schenectady, N. Y.

Moore, J. M. (Member), United Illuminating Company, New Haven, Conn.

Murchison, H. E., Simplex Wire and Cable Company, Cambridge, Mass.

Oberhelman, O. F., Jr., General Electric Company, Schenectady, N. Y.

Persson, J. A., Electrometallurgical Company, Niagara Falls, N. Y.

Pickard, J. K., General Electric Company, Schenectady, N. Y.

Pierson, E. T., General Electric Company, Bridgeport, Conn.

Poklepovic, D. P., General Electric Company, Schenectady, N. Y.

Ritchie, J. S., General Electric Company, Schenectady, N. Y.

Robinson, J. A., General Electric Company, Schenectady, N. Y.

Rudahl, A. E., Electrolux Corporation, Old Greenwich, Conn.

Ruibal, A., Union College, Schenectady, N. Y.

Swanson, M. C. (Associate re-election), American Locomotive Company, Schenectady, N. Y.

Sylvester, R. B., Lyndon Center, Vt.

Van Valkenburg, H. E., General Electric Company, Schenectady, N. Y.

Veronda, C. M., General Electric Company, Schenectady, N. Y.

Wardell, E. R., General Electric Company, Schenectady, N. Y.

West, C. F., Radiation Laboratories, Massachusetts Institute of Technology, Cambridge, Mass.

Williams, C. E., General Electric Company, Schenectady, N. Y.

Wilson, R. E., General Electric Company, Schenectady, N. Y.

Winkle, L., U.S.N.R., Massachusetts Institute of Technology, Cambridge, Mass.

Zimmele, C. M. (Associate re-election), Vought-Sikorsky Air Craft, Stratford, Conn.

2. Middle Eastern

Abramowitz, S., Philadelphia Signal Corps, Inspection Zone, Philadelphia, Pa.

Andreasen, I. E., General Electric Company, Erie, Pa.

Appleton, E. B., Naval Ordnance Laboratory, Washington, D. C.

Bass, P. B. (Member), Public Service Electric and Gas Company, Trenton, N. J.

Berger, H. J., American Telephone and Telegraph Company, Cleveland, Ohio.

Blashfield, W. H., North Electric Manufacturing Company, Galion, Ohio.

Boyer, J. L., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Bradshaw, F. C., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Brane, M. D. (Member), C. H. Hunt Company, Pittsburgh, Pa.

Brown, C. M., Jr., RCA Manufacturing Company, Inc., Camden, N. J.

Burke, J. T., Naval Research Laboratory, Washington, D. C.

Cham, E. J., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Chandler, H. M., Jr., Princeton University, Princeton, N. J.

Cherrick, I. L., Naval Research Laboratory, Bellevue, D. C.

Cooper, M. D. (Member), Fenn College, Cleveland, Ohio.

Cornelius, J. H., Brown and Heim, Inc., Baltimore, Md.

Cummins, S. M., 854 Rumsey Avenue, Erie, Pa.

Darr, J. E., Bethlehem Steel Company, Johnstown, Pa.

Davis, P. A. (Member), War Department, Signal Corps, Washington, D. C.

Deckelmann, L. M., Navy Dept., Bureau of Ships, Washington, D. C.

Douglas, G. R., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Eberstein, C. F., General Electric Company, Erie, Pa.

Edison, E., RCA Manufacturing Company, Camden, N. J.

Edmunds, W. H., I-T-E Circuit Breaker Company, Philadelphia, Pa.

Edwards, A. W., Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

Ellerman, H. E., Jr., Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

Ferdig, R. G., Navy Department, Bureau of Ships, Washington, D. C.

Ferris, F. H., Jr., Pennsylvania Transformer Company, Pittsburgh, Pa.

Foster, J. H., Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.

Frandsen, L. N., Westinghouse Electric and Manufacturing Company, Baltimore, Md.

Gaubecca, J. B., Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

Godwin, G. L., Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

Harden, H. B., Stone and Webster Engineering Corporation, Williamsport, Pa.

Harris, R., New Zealand Supply Mission, Washington, D. C.

Hellon, J. B., RCA Manufacturing Company, Camden, N. J.

Holzman, G. R., Naval Research Laboratory, Washington, D. C.

Hull, W. O. (Associate re-election), Line Material Company, Zanesville, Ohio.

Husbands, L. D., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Huttinger, F. X., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Isakson, F. B., Bureau of Ships, Navy Department, Washington, D. C.

Jaberg, H. A., Ohio Inspection Bureau, Cincinnati, Ohio.

Jenkins, J., Case School of Applied Science, Cleveland, Ohio.

Johnson, C. Y., U.S.N.R., Naval Research Laboratory, Anacostia Station, Washington, D. C.

Jones, R. C., Jr., Aircraft Radio Laboratory, Wright Field, Dayton, Ohio.

Jones, W. B., 3323 East Street, N. S., Pittsburgh, Pa.

Kelly, J. M., Jr., Naval Research Laboratory, Anacostia Station, Washington, D. C.

Kelso, F. (Associate re-election), Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.

Kerr, N. F., Pennsylvania Transformer Company, Pittsburgh, Pa.

Ketch, W. E., Westinghouse Electric and Manufacturing Company, Wilkinsburgh, Pa.

Linton, R. L., Jr., Naval Research Laboratory, Anacostia Station, Washington, D. C.

McCabe, G. C. (Member), Potomac Electric Power Company, Washington, D. C.

McCleery, E. C., United States Engineers, Washington, D. C.

Meyer, C. F., Jr., General Electric Company, Erie, Pa.

Meyers, B. C. H., Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Morgen, M., National Union Radio Corporation, Lansdale, Pa.

Moritz, C., Philco Radio and Television Corporation, Philadelphia, Pa.

Munnikhuysen, R. D., U. S. Army Air Forces, Material Center, Wright Field, Dayton, Ohio.

Niesink, T., University of Pittsburgh, Pittsburgh, Pa.

Opeka, F., Dravo Corporation, Pittsburgh, Pa.

Paden, C. O., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Panoff, R., United States Navy Department, Bureau of Ships, Washington, D. C.

Parchman, J. B., Sylvania Electric Products, Inc., Emporium, Pa.

Parrish, W. F., 2017 Edgewood Street, Baltimore, Md.

Paskevich, A. F., Pennsylvania Power and Light Company, Allentown, Pa.

Perkins, C. H., U. S. Army Air Corps, Wright Field, Dayton, Ohio.

Peters, R. R. (Member), United States Naval Reserve, Navy Yard, Philadelphia, Pa.

Posner, A. W., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Richmond, J. K., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Roccati, E. J., Chesapeake and Potomac Telephone Company, Washington, D. C.

Rough, L. W. (Associate re-election), Carbide and Carbon Chemicals Corporation, South Carleston, W. Va.

Rudnicki, A. J., U.S.N.R., c/o Crosley Corporation, Cincinnati, Ohio.

Rueggeberg, W., 408 Westgate Road, Baltimore, Md.

Sahn, P. A. B. (Member), Koppers Company, Pittsburgh, Pa.

Schneider, N., RCA Manufacturing Company, Camden, N. J.

Schoenberg, M. J., General Motors, Trenton, N. J.

Seaman, E. F. (Member), Bureau of Ships, Navy Department, Washington, D. C.

Shaffer, C. G., Western Electric Company, Baltimore, Md.

Shallcross, J. S., Shallcross Manufacturing Company, Collingsdale, Pa.

Sheahy, A. N. (Member), Pennsylvania Water and Power Company, Baltimore, Md.

Smith, S. T., Naval Research Laboratory, Washington, D. C.

Stampley, N. L., Naval Research Laboratory, Washington, D. C.

Stoughton, M. L., I-T-E Circuit Breaker Company, Philadelphia, Pa.

Wahl, A., Air Corps, U. S. Army, Wright Field, Dayton, Ohio.

Warner, R. C., Consolidated Gas Electric Light and Power Company, Baltimore, Md.

West, K. L., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

White, R. A., Princeton University, Princeton, N. J.

Whitworth, D. G., Kelly Springfield Engineering Company, Cumberland, Md.

Wilcox, G. L., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Wilkinson, W. R., Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Williams, C. R., Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Woodhull, J. H., Federal Communications Commission, Washington, D. C.

Wouk, V., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

3. New York City

Balchan, S. J., American Telephone and Telegraph Company, New York, N. Y.

Bartolotta, J. J., Signal Corps, Ft. Monmouth, N. J.
Bechtel, W. W., American Type Founders, Elizabeth, N. J.
Birsten, B. R., Solar Manufacturing Corporation, Bayonne, N. J.
Blincoe, L. R. (Associate re-election), General Electric Company, Newark, N. J.
Bolton, R. (Member), National Electric Company, Passaic, N. J.
Blom, G. E., Long Island Lighting Company, Glenwood Landing, N. Y.
Cohen, P., War Department, Camp Evans, Belmar, N. J.
Davis, C. M., Postal Telegraph-Cable Company, New York, N. Y.
Duffy, E. K., General Cable Company, Bayonne, N. J.
Duguid, D. S., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Dunlop, J. N., Jr., 122 East 82d St., New York, N. Y.
Friedman, E. D., Federal Telephone and Radio Corporation, Newark, N. J.
Furlong, J. F., Jr., Western Electric Company, New York, N. Y.
Gilmore, G. E., USS Prairie State, New York, N. Y.
Hayman, W. H., Press Wireless, Incorporated, Hicksville, N. Y.
Horn, H. H., Arma Corporation, Brooklyn, N. Y.
Joy, C. R., Jr., Signal Corps, Ft. Monmouth, N. J.
Kelly, F. G. (Member), Thomas A. Edison, Incorporated, West Orange, N. J.
Konigsberg, R. L., Western Electric Company, Kearny, N. J.
Kors, S. M., American Telephone and Telegraph Company, New York, N. Y.
Martin, M., Lone Star Steel Company, New York, N. Y.
McClenahen, R. A. (Member re-election), Public Service Electric and Gas Company, Newark, N. J.
Moulton, W. H., National Union Radio Corporation, Newark, N. J.
Ostrolenk, S., 10 East 40th Street, New York, N. Y.
Paterson, A. H. (Member), War Department, New York Ordnance District, New York, N. Y.
Peskin, E., Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
Platt, C. J., Wilputte Coke Oven Corporation, New York, N. Y.
Sanderson, C. M., Jr., 324 Meadowbrook Lane, So. Orange, N. J.
Sanial, A. J. (Member), Powers Electronic and Communication Company, Glen Cove, N. Y.
Secls, H. F. (Associate re-election), Sperry Gyroscope Company, Incorporated, Brooklyn, N. Y.
Selgin, P. J., Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
Simmonds, R. L., Signal Corps, U. S. Army, Fort Monmouth, N. J.
Stamatov, G. (Associate re-election), Consolidated Edison Company, New York, N. Y.
Struven, D. J. (Associate re-election), Westinghouse Lamp Division, Bloomfield, N. J.
Waldron, J. E., Nicaro Nickel Company, New York, N. Y.
Weiller, P. G., Square D Company, Woodside, L. I., N. Y.
Wheeler, R. B., 36 Catalpa Avenue, Hackensack, N. J.
Wilkie, A. C., Jr., 490 Port Washington Blvd., Port Washington, N. Y.
Woods, R. J., Sperry Gyroscope Company, Incorporated, Brooklyn, N. Y.
Woodworth, J. D., Signal Corps General Development Laboratory, Fort Monmouth, Red Bank, N. J.
Wright, F. E. (Associate re-election), 30 Church Street, New York, N. Y.
Yeager, J. R., American Telephone and Telegraph Company, New York, N. Y.
Yor, H. A. (Member re-election), Bendix Aviation Corporation, Brooklyn, N. Y.

4. Southern

Brauneck, C. F., Signal Corps, Camp Murphy, Fla.
Buck, J. R., U. S. Navy Department, Pascagoula, Miss.
Chatham, O. L., U.S.E.D., Tampa, Fla.
Cooke, S., U. S. Army Air Corps, Communications Detachment, Tuskegee, Ala.
Cross, J. Memphis Light Gas and Water Division, Memphis, Tenn.
Duncan, W. A., Kentucky Utilities Company, Lexington, Ky.
Egee, J. W. (Associate re-election), Bull Dog Electric Products Company, New Orleans, La.
Evans, T. F., Hercules Powder Company, Radford, Va.
Funderburk, M. M., Louisiana Power and Light Company, Sterlington, La.
Gardberg, J., Gulf Shipbuilding Corporation, Chickasaw, Ala.
Hite, J. L., Kentucky Utilities Company, Lexington, Ky.
Jennings, H. F., Tennessee Valley Authority, Knoxville, Tenn.
Kerr, W., Jr., University of Tennessee, Knoxville, Tenn.
Newby, D. H., National Advisory Committee for Aeronautics, Langley Field, Va.
Patrick, W. A., General Electric Supply Corporation, Louisville, Ky.
Smith, E. A., U. S. Army, Ordnance Department, Ft. Myers, Fla.
Sprouse, M. N., Tennessee Valley Authority, Knoxville, Tenn.
Strode, V. C., Jr., Signal Corps, Air Force, Tampa, Fla.
Stuart, B. B. (Member), Navy Department, Navy Yard, Charleston, S. C.
Thomas, G. S., United States Navy Yard, Charleston, S. C.
Waite, C. T., Jr., Army Air Corps, Barksdale Field, La.
Westermeyer, C. H., 118th Signal Radio Intelligence Co., Camp Forrest, Tenn.

5. Great Lakes

Abramson, J. E., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Andes, S. I., Lake Machinery Company, Chicago, Ill.
Carpenter, H. A., 512 West South Street, Angola, Ind.
Davidson, C. P., RCA Victor Division, Radio Corporation of America, Indianapolis, Ind.
Ellis, H. N., 246 Waubesa Street, Madison, Wis.
Flaugh, F. C., Jr., Chicago Signal Corps Inspection Zone, Chicago, Ill.
Healy, C. F., 408 West Lyon Street, Marshall, Minn.
Kumm, E. L., Dow Chemical Company, Midland, Mich.
Larson, C. J. (Associate re-election), Commonwealth Edison Company, Chicago, Ill.
Larson, L. R., Iowa State College, Ames, Iowa.
Marchant, T. E., 801 Jefferson Street, Gary, Ind.
Michals, R. J., Minneapolis-Honeywell Regulator Company, Minneapolis, Minn.
Mortley, J. T., Ford Motor Company, Dearborn, Mich.
Naylor, M. W., 338 West 30 Street, Davenport, Iowa.
Petermann, F. C., U. S. Signal Corps, Electronics Division, University of Chicago, Chicago, Ill.
Pinsky, J. D., Museum of Science and Industry, Chicago, Ill.
Polcyn, S. J., Jr., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Reese, K. E., Zenith Radio Corporation, Chicago, Ill.
Reilly, E. L. (Associate re-election), U. S. Maritime Commission, Chicago, Ill.
Schaller, W. F. (Member), Marquette Electric Switchboard Company, Chicago, Ill.
Schneider, C. L., Ordinance Steel Foundry Company, Betendorf, Iowa.
Staats, G. W., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Standish, M. E., Carnegie-Illinois Steel Corporation, Chicago, Ill.
Thomas, J. H., 1135 Robertson Street, Wawuatosa, Wis.
Whitehead, L. E. (Associate re-election), Commonwealth Edison Company, Chicago, Ill.
Willson, E. A. (Associate re-election), Northern States Power Company, Minneapolis, Minn.
Yates, R. E., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.

6. North Central

Nitta, R. Y., Del Norte, Colo.
Tarr, A. R., Colorado Central Power Company, Englewood, Colo.
Winslow, W. M., Public Service Company of Colorado, Denver, Colo.
Yewell, P. G., U. S. War Department, Fowler, Colo.

7. South West

Adams, P. E., Jr., Signal Corps, U. S. Army, Fort Sill, Okla.
Blanchette, V. G., Consolidated Steel Corporation, Ltd., Orange, Tex.
Carson, G. M., Dennis, Kan.
Curry, E. M., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Haas, P. A. (Associate re-election), Board of Public Utilities, Kansas City, Kan.
Howell, A. L., Consolidated Steel Corporation, Ltd., Orange, Tex.
Moder, E. C., Jr., Rural Electrification Administration, St. Louis, Mo.
Money, L. J., Rice Institute, Houston, Tex.
Palmer, J. P., 2152 Watts Road, Houston, Tex.
Robinson, F. H. (Member), Rural Electrification Administration, St. Louis, Mo.
Shepherd, N. H., Box 726, Altus, Okla.
Staft, V. E. (Member), Naval Ammunition Depot, McAlester, Okla.
Sumner, G. C., 315 Chicago Street, Fort Worth, Tex.
Vreeland, W. N., Jr., Thomas A. Edison, Incorporated, St. Louis, Mo.
Watkins, B. O., Rural Electrification Administration, St. Louis, Mo.
Weschelmer, E. G., Southwestern Bell Telephone Company, Houston, Tex.
Woobey, D. L., Signal Corps, Camp Crowder, Mo.

8. Pacific

Ardery, J. E., Consolidated Aircraft Corporation, San Diego, Calif.
Bales, W. L., 208—23rd Avenue, San Mateo, Calif.
Bulkley, O. R. (Associate re-election), Southern California Edison Company, Limited, Los Angeles, Calif.
Caldwell, F. R., 1617 N. Dayton Street, Phoenix, Ariz.
Chang, T. C., W. A. Bechtel Company, Sausalito, Calif.
Doolittle, O. L., Southern California Telephone Company, San Diego, Calif.
Edward, A. W., R.N.V.R., British Admiralty, British Ministry of War Transport, San Francisco, Calif.
Enefer, J. D., Southern California Edison Company, Limited, Los Angeles, Calif.
Fleager, W. M., Pacific Telephone and Telegraph Company, Oakland, Calif.
Geisendorfer, H. A., Jr., Richmond Shipyard No. 1, Richmond, Calif.
Gerckens, C. H., Cole Electric Company, Los Angeles, Calif.
Goetz, J. A., Jr., N.A.C.A., Ames Aeronautical Laboratories, Moffett Field, Calif.
Hoffman, O. W., General Electric Company, Oakland, Calif.
Kaprielian, E. F., U. S. Navy, Terminal Island, Calif.
Moeller, R. A., Taypro Corporation, San Francisco, Calif.
Nahapiet, E. O. (Associate re-election), Austin W. Earl, San Francisco, Calif.
Proppe, H. L., Jr., Westinghouse X-Ray Division, San Francisco, Calif.
Read, R. F., Sundt Construction Company, Tucson, Ariz.
Richey, R. R., Westinghouse Electric and Manufacturing Company, San Diego, Calif.
Rutherford, C. E., Lockheed Aircraft Corporation, Burbank, Calif.
Samter, J. H., Dow Chemical Company, Pittsburg, Calif.
Stewart, R. R. (Associate re-election), Joslyn and Ryan, San Francisco, Calif.
Syron, R. O., Signal Corps, Service Command, c/o Postmaster, San Francisco, Calif.
Talbott, W. H., Jr., Westinghouse Electric and Manufacturing Company, Los Angeles, Calif.
Veit, W. A., 819 No. Olive Avenue, Alhambra, Calif.
Walsh, W. C. (Associate re-election), United States Department of Agriculture, Farm Security Administration, San Francisco, Calif.
West, G. P., P.O. Box 152, Sunol, Calif.
Wilson, G. A., Barrett and Hilp, Hunters Point Drydocks, San Francisco, Calif.

9. North West

Ashleman, F. C., 18th Coast Artillery, Fort Stevens, Oreg.
Bodine, F. E., Westinghouse Electric and Manufacturing Company, Salt Lake City, Utah.
Bruce, E. C., 845 Engr. Avn. Bn., Geiger Field, Spokane, Wash.
Fincher, E. H., Westinghouse Electric and Manufacturing Company, Seattle, Wash.
Greiling, R. D., 7542 North Commercial Avenue, Portland, Oreg.
Lindberg, B. G., 1823 South Grand Boulevard, Spokane, Wash.
Mackenzie, N. (Member), Colville Engineering Company, Colville, Wash.
McDowell, J. M., Signal Corps-Reserve, U. S. Army, Seattle, Wash.
McGill, C. S. (Member), Montgomery Electric Company, Portland, Oreg.
Purcell, J. L. A. (Member), United States Engineer Office, War Department, Seattle, Wash.
Retherford, R. W., Naval Training School, University of Idaho, Moscow, Idaho.

10. Canada

Bailey, F. G., Bell Telephone Company, Toronto, Ont.
Bradfield, A. W., Canadian General Electric Company, Ltd., Peterborough, Ont.
Comach, S. I. (Member), Royal Canadian Navy, Ottawa, Ontario, Canada.
Fisher, S. T. (Member), Northern Electric Company, Ltd., Montreal, Quebec.
Kidd, K. H., Royal Canadian Engineers, Canadian Army, Brockville, Canada.
Lillie, B. A., Hydro Electric Power Commission o Ontario, Toronto, Ont.
MacDonald, W. P. (Member), Nanaimo-Duncan Utilities, Ltd., Nanaimo, B. C.
Mitchell, D. A., Hydro-Electric Power Commission, Burlington, Ont.
Schofield, L., Canadian Westinghouse Company, Limited, Montreal, Quebec.
Southam, W. W., Vancouver Daily Province, Vancouver, B. C., Canada.
Tallman, A. M., English Electric Company, St. Catharines, Ont.

Total, United States and Canada, 311

Elsewhere

Bird, F. V. G. (Member), Central Electricity Board, London, W.C. 2, England.
Bryant, A. C. (Member), Messrs. Johnson and Phillips Limited, London, S.E. 7, England.
Cory, F. P., Painton and Company Limited, Northampton, England.
Gonzalez, E. F. A., Cristo, Ote., Cuba.
Grobler, P. S. (Associate re-election), Provincial Administration, O.F.S., Kroonstad, South Africa.
Menezes, R., Compania Mexicana de Luz y Fuerza, Juarez, Mexico.
Zift, M. L., Johnson and Phillips Limited, Victoria Way, Charlton, S.E. 7, London, England.

Total, elsewhere, 7

OF CURRENT INTEREST

Royal Electrical and Mechanical Engineers Corps Established by British Army

Electrical and mechanical engineering maintenance for the British Army has been brought under single control by the formation of the Royal Electrical and Mechanical Engineers. The unit is described in the ensuing news item which was prepared for publication in *Electrical Engineering* by Owen Pawsey, former editor of *Electrical Trading* and former member of the editorial staff of *Broadcaster*, both British periodicals.

This new corps, which came into being officially on October 1, 1942, is the complete engineering-maintenance wing of the British land forces, with the exception of civil engineering. Functions of the corps are:

1. The inspection and maintenance of tanks, wheeled vehicles, all artillery (including field, antiaircraft, and coast defense), small arms and machine guns, radio and line communication equipment, radiolocation (radar), fire control and other instruments, tunneling equipment, pumping sets, and the installation of coast-artillery machinery.

2. Repairs made necessary by ordinary wear and tear or battle casualties.

3. Investigations into defects in design and recommendations for improvements.

4. Advice on prototype design in relation to maintenance work.

NEW CORPS AIDS EFFICIENCY

Prior to the formation of the REME, responsibility for engineering maintenance and repairs was split up. The bulk of the work previously was under the control of the Royal Army Ordnance Corps, but there were also large technical sections in the Royal Engineers and the Royal Army Service Corps, and further smaller groups of skilled engineers elsewhere. One result of this spread-out setup was a lack of unified direction on technical maintenance at the British War Office.

Each unit had evolved its separate control and methods for engineering maintenance, and as these were administered alongside many other matters completely unrelated to engineering, the channels of control frequently included nontechnical personnel. This sometimes resulted in delay and distortion of technical matters the importance of which had not been appreciated or understood fully.

Further disadvantages were that the equipment used for testing and repair had to be well dispersed among the various Army units, and skilled tradesmen were not always employed fully in those duties for which they were qualified.

These disadvantages have been rectified in the REME organization, which combines the necessary centralized control with a fluid system providing quick and efficient maintenance for all electrical and mechanical equipment. The nucleus of the corps consists of the technical sections of the Royal Army Ordnance Corps, Royal Engineers, and Royal Army Service Corps already mentioned. At an early date appropriate personnel of the Royal Artillery, Royal Armored Corps, and Royal Signals are also to be incorporated.

Major General Eric Bertram Rowcroft, an engineer of wide civil and military experience, controls the REME from the War Office, where there is direct and equal representation of all technical matters. From him extends a complete chain of coordination of engineering personnel passing down through deputy directors to the electrical and mechanical engineer, who acts as technical adviser to the brigade commander in the field. This system ensures that on matters of general strategy, tactics, and operations there are REME experts at all stages to see that engineering technical equipment and personnel are adequately provided and employed.

Alongside this "policy channel," the REME has its own direct approach to and from the headquarters staff of the War Office on all domestic questions. Although attached to every unit in the Army which uses mechanical or scientific equipment the REME is autonomous in the control of its men and this latter channel is employed for that purpose. It also ensures that maintenance procedure is transmitted quickly and efficiently and that any questions that may arise on purely technical affairs are brought to the notice of higher officials who are able to understand them, value them properly, and obtain decisions with the least possible delay.

A further function of this channel is to give officers and men of the new corps a voice in prototype design. Such advice is confined to engineering maintenance and the study of related defects of equipment, although, of course, full design is encouraged in the case of equipment needed in the course of testing, repairing or inspecting of army gear.

SPECIALIZATION

To permit full specialization the corps is divided into several branches. On the electrical side there are three branches: first, "telecommunications," an omnibus word adopted to cover radar, radio, and wire; second, there is the light electrical section which has the care of the Army instruments and specialized equipment such as searchlights; third, the heavy electrical section, which corresponds to power engineering in civil life. Automobile electricity is the responsibility of the vehicle branches (armored fighting vehicles and transports).

Whereas specialization is an advantage in the upper strata of the corps and among the mechanics and engineers in the noncommissioned ranks, it is unnecessary and

British Ministry of Information

Radio mechanics of the Royal Electrical and Mechanical Engineers service British Army apparatus at a base workshop

even inadvisable in the lower commissioned ranks. Officers who have charge of men actually in the combat zone are required to have general knowledge both of electrical and mechanical engineering and all their training is planned with that in view.

At present men having the requisite qualifications to obtain direct entry into the corps are scarce. British industry already has had to give up all its qualified technical men below the age of 25 years.

NONCOMMISSIONED RANKS

As in the case of officers, so in the case of noncommissioned ranks, the REME has adopted a full scheme of college and field training, which in present circumstances is condensed into a period of nine months. The course for commissioned ranks corresponds to normal "continuation" classes; it assumes a fundamental practical knowledge of electricity, mechanics, or electronics and instructs in particular applications to warfare.

Wherever possible the noncommissioned ranks are drawn from men who already have had experience as electricians, radio service mechanics, power linesmen, and similar occupations, and such men have opportunities to obtain immediate rank as sergeant-artificer on finishing their army course. The "private", known in the REME by the new rank of craftsman, is mostly recruited from inexperienced men who show an interest in mechanical or electrical work. The rates of pay throughout the corps are generally on a higher scale than those of the other Army units.

Parker Dam Begins Operation in Southwest

The newest large Bureau of Reclamation hydroelectric power plant, the Parker Dam plant in California–Arizona on the Colorado River, has begun generating power and will be operating at maximum capacity of 120,000 kw by next May, ten years ahead of the originally scheduled time, according to a recent announcement. This is the 29th hydroelectric development placed in operation by the Bureau in 40 years.

This new plant, which is supplying energy for war industry, mining operations, and military use in the Pacific Southwest, already has three 30,000-kw generators completed, two of which started commercial operation in December, and one scheduled to begin later; the fourth generator is expected to begin operation in May.

Parker Dam has as a primary purpose the diversion of water from the Colorado River for the Metropolitan Water District of Southern California, a group of 13 cities in the Los Angeles metropolitan area. The Metropolitan Water District financed the construction of Parker dam, and is entitled when it requires the power, to one half of the output from the power plant. Total maximum available output is quoted as 600,000,000 kilowatt-hours of electric energy annually. Title to the dam is in the United States.

Horsepower of Electric Motors Restricted by WPB

The horsepower of a new electric motor may not exceed the requirements of the specific job for which the motor is purchased, according to a recent provision in the War Production Board general conservation order L-221.

To prohibit the former industrial practice of applying greater motor capacity than necessary for the job to be done, the order prohibits the delivery or acceptance of motors, unless they comply with certain standard specifications and are of the simplest practicable mechanical and electrical design. It also requires the purchaser to certify and show reason why he must have a motor of a special type; and it restricts the use of such special types to the conditions and the purposes for which they are required. For example, it limits the use of explosionproof motors to hazardous locations.

One of the important conservation provisions in the order, which applies to both motors and generators, requires the applicant to certify that he has made every reasonable effort

1. To adapt idle motors or generators in his possession.
2. To obtain used ones for his purpose.
3. To repair or recondition his existing equipment.

If one cannot secure used equipment within a reasonable time, one may apply to the WPB Surplus Used Equipment Branch for assistance.

The order is expected to save annually about 15,000,000 pounds of copper, 55,000 tons of carbon steel, and 150,000 pounds of stainless steel.

The Navy Needs Engineers for Electronic Work

The United States Navy Department recently issued the following request for engineering personnel:

"The rapid expansion in Navy surface vessels, submarines, and aircraft has created several hundred additional billets for officers trained in electrical engineering who are needed to serve in engineering work in connection with ultrahigh-frequency electronic apparatus, the Navy announced recently.

"The Navy has issued a call for qualified engineers to fill the new vacancies. Technically qualified for this work are men who hold degrees in electrical engineering and have practiced in the field of engineering since their graduation; or men who have majored in physics, mathematics, or other branches of engineering and who have acquired a sound working knowledge of a-c circuits and electronics.

"Men commissioned for this electronic work are given the Navy's three-months' course in ultrahigh frequencies at either Harvard University or Bowdoin College, followed by an additional three-months' laboratory course at Massachusetts Institute of Technology. Upon graduation, these officers are assigned to responsible engineering positions having to do with research, design, instruction, or maintenance of the Navy's ultrahigh-frequency equipment.

"Qualified engineers are urged to apply for a commission at the nearest Office of Naval Officer Procurement. These offices are located in principal cities throughout the United States."

TVA Reports Progress During Past Year

Tennessee Valley Authority began construction of eight dams for war production of power, continued work on three % dams on shortened wartime schedules, and started operation on four dams and a large steam plant during the fiscal year, according to the annual report to the President and Congress. About 500 miles of transmission lines were built, increasing the network by ten per cent, and a major interconnection with power systems to the north was effected, making possible more efficient use of power facilities in the TVA and adjoining areas.

A large ammonium nitrate plant, with a newly constructed synthetic ammonia plant to supply raw materials, was placed in service to produce an ingredient of high explosives for the War Department. Another plant used in peacetime for production of phosphatic fertilizers was enlarged and equipped to produce elemental phosphorus for the Chemical Warfare Service. TVA now has one fourth of the Nation's capacity for production of munitions-grade phosphorus.

Completion of dams during the year brought the navigation channel on the Tennessee to four fifths of its ultimate 650-mile length, and flood control storage in the Authority's reservoirs was increased to 6,000,000 acre-feet, an increase of 2,000,000 acre-feet.

Slide-Films for First Aid Issued. First-aid slide-film kits designed to assist in first-aid training programs conducted on a company-wide scale are now available. The film-strip kit includes 20 individual slide-film subjects (averaging 70 individual pictures each) in technicolor; 14 records containing 20 correlated voiced lectures to be used with the films; 20 printed lesson guides for student study, and an instructor's manual showing how to conduct the classes. Although it is not intended that the slide-film kit alone should train the class completely, but rather add to lecture, textbook, and demonstration, the use of the kit makes it possible to conduct an approved and official course in less time than is required ordinarily by lecture, demonstration, and textbook alone. The film strips may be projected in any slide-film projector equipped with a record turntable. All inquiries should be addressed to the distributors, the Jam Handy Organization, 2900 East Grand Boulevard, Detroit, Mich.

Armor Rod Patents Given to Public. Patents for armor rods, previously employed chiefly with a single type of transmission-line cable, recently were made available to the public for all conceivable uses and without the need for licensing procedure, when a deed of public dedication was filed by Aluminum Company of America in the United States Patent Office, Washington, D. C. The patents made available to the public are numbers 1,639,820 and 1,873,798. Armor rods resemble an extra layer of heavy strands and are used to cover the cable for a short distance at points of support.

INDUSTRY

Graduate Evening Courses Being Given in Industrial Plant

Graduate evening extension courses in advanced electronics, electromagnetic-wave theory, and ultrahigh-frequency phenomena are being conducted at the Garden City plant of the Sperry Corporation by staff members of the department of graduate study and research in electrical engineering, Brooklyn Polytechnic Institute.

Courses currently being conducted by the school at Garden City include: Advanced-circuit theory by Ernst Weber (F '34), head of the graduate electrical engineering department; fundamentals of radio by William A. Lynch (sponsored by the government Engineering, Science, and Management War Training program); and two other ESMWT courses under the direction of George B. Hoadley (M '41). Specific applications of the theories to the day-to-day work at the plant are taught by Henry Harris of the Sperry Corporation under the direction of Ralph Carlson, director of employe training at the Garden City plant.

Positions to Be Filled Through Civil Service

The United States Civil Service Commission is accepting applications for the following engineering positions until further notice. Because of the urgent need for engineers, written tests and age limits have been abandoned for these positions. Applicants will be judged on education and experience. Applications and complete information may be obtained at any first- or second-class post office, except in regional headquarters cities, where they are available, only at the civil service regional office, or from the United States Civil Service Commission, Washington, D. C. War man-power restrictions on Federal appointments are also posted in first- and second-class post offices. Vacancies in Washington, D. C., throughout the United States, and in the territories and possessions of the United States are to be filled.

Assistant Engineer ($2,600 a year salary) through *chief engineer* ($8,000 a year salary). This position requires the completion of a full four-year course leading to a bachelor's degree in engineering in a college or university of recognized standing. Professional engineering experience providing the substantial equivalent of such a course may be substituted for the foregoing educational requirement. In addition one year of professional engineering experience or of engineering graduate study is required for the position of assistant engineer at $2,600. For more advanced positions, applicants must show additional experience of a progressively higher level.

Junior engineer ($2,000 a year salary). No experience is necessary. College graduates with a degree in any field, who are enrolled or willing to enroll in the Engineering, Science, and Management War Training Course in engineering fundamentals, sponsored by the United States Office of Education, may apply.

Radio inspectors ($2,600 and $2,000 a year salaries.) Needed for employment in the Federal Communications Commission. Study at a college or university of recognized standing, technical experience in radio work, or a combination of the two will be accepted as preparation for these positions. Amateur radio experience under a class *A* license may be substituted as part of the experience requirement. In addition, applicants must hold a valid second-class radiotelegraph operator's license, or demonstrate their ability to transmit and receive 16 code groups per minute in International Morse Code, and be able to drive an automobile.

Westinghouse Fellowships Suspended. Ten research fellowships, awarded annually by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., have been discontinued until after the war. The fellowships were established in 1937 for research in physics, making possible a study of the scientific problems confronting the electrical industry. The company plans to continue only that research directed toward aiding the war effort. However, it has been announced that the company is interested in employing men who normally would be eligible for the fellowships, thereby enabling young scientists more quickly to find a place in the war activities now under way.

OTHER SOCIETIES

AIME Lucas Medal Awarded

The Anthony F. Lucas Gold Medal for 1943 of the American Institute of Mining and Metallurgical Engineers has been awarded to John Robert Suman, vice-president of the Humble Oil and Refining Company, Houston, Tex., for his "distinguished achievement in improving the technique and practice of producing petroleum." The oil-producing research carried on under Doctor Suman's direction is said to have revolutionized production methods and to have established oil-reservoir engineering on a sound foundation. It is estimated that the efficiencies and the economies made possible by this research have cut oil-producing costs almost in two and have doubled the proportion of recoverable oil.

Doctor Suman was born in Daleville, Ind., on April 9, 1890, and was graduated from the School of Mines, University of California, Berkeley in 1912. Almost his entire professional work has been in the oil-producing industry.

Future Meetings of Other Societies

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 14–18, 1943, New York, N. Y.

American Railway Engineering Association. Annual Convention, March 16–18, 1943, Chicago, Ill.

American Society for Testing Materials. Spring meeting, March 2–5, 1943, Buffalo, N. Y.; annual meeting, June 28–July 2, 1943, Pittsburgh, Pa.

Engineering Institute of Canada. 57th annual meeting, February 11–12, 1943, Royal York Hotel, Toronto, Canada.

National Electrical Manufacturers Association. Spring meeting, April 20–23, 1943, Chicago, Ill.

Melville Medal Award Announced. The Melville Medal, awarded annually by American Society of Mechanical Engineers for the most original paper on a mechanical-engineering subject, has been presented to J. Kenneth Salisbury, of the turbine engineering department of the General Electric Company, Schenectady, N. Y., for his paper, "The Steam Turbine Regenerative Cycle—an Analytical Approach." Mr. Salisbury received the degrees of bachelor of science in 1929 and master of science in mechanical engineering in 1930 from the University of Michigan. He has been employed by the General Electric Company since 1930.

New Sections Formed by NEMA. The formation of an electronics section and an industrial and commercial lighting equipment section has been announced by the National Electrical Manufacturers Association. The electronics section will seek to establish a maximum use of the electronic science in winning the war and in rebuilding the world after the war. The commercial lighting section will try to effect the fullest and best employment of lighting in the war effort.

EDUCATION

Northwestern's Technological School Receives Liberal Bequest

A bequest in excess of $20,000,000 to be used as a fund to develop, maintain, and operate its technological institute will be given to Northwestern University from the estate of Walter P. Murphy, manufacturer of railway supplies, who died December 16, 1942. The university will receive the entire estate after payment of bequests to relatives and friends.

The technological institute of Northwestern University was founded in 1939 by a gift of $6,735,000 from the Walter P. Murphy Foundation. Mr. Murphy had made two additional gifts to this university, $5,000 to the college of liberal arts and $10,000 to the school of commerce in 1923.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without letter, the other lettered. Captions should be supplied for all illustrations.

Detecting the Saboteur—Static Electricity—in Gasoline Fires

To the Editor:

Questions regarding hazards due to static electricity are continually arising in industry. The choice of a "cure" is sometimes either ineffective or in some cases more hazardous than the condition existing before application of the "cure."

Studies have been made of static generation and its removal in some types of industrial operations. In many cases such studies have been sufficiently broad to find direct application in other fields. In many cases, however, the best solutions for the problems have not been published.

Do you think this subject could be handled by the Institute as a seminar at one of the meetings? Could the Institute be prevailed upon to prepare a critical study and bibliography of the published articles? Such a subject should be very timely considering the hazards associated with operations carried on in wartime.

In this regard, we read with interest the article, "Detecting the Saboteur—Static Electricity—in Gasoline Fires," by Robin Beach in the October 1942 issue of *Electrical Engineering*, pages 501–8.

In this article there is one point that forms the basis of the solution of the author's first case but does not appear to be valid.

In Figure 1 he shows the tank as one capacitance and the tank truck as a capacitance in series with a second capacitance comprising the surface of the roadway as an equipotential surface and the base of the roadway at ground potential as the second plate of the series-capacitance combination.

The resistance of the roadway tires is high, so that in effect it appears that the tank truck to ground could be treated as a single capacitance.

If this were the case, the tank could be brought to the potential of the truck practically instantly when the grounding wire from the truck was connected to the tank. This would, of course, reduce the voltage to ground of the truck by virtue of charging the tank which is assumed to be 500 micromicrofarads. If the truck is 1000 micromicrofarads, the potential of the truck to ground would be two thirds the initial voltage of the truck.

This, admittedly, is the extreme case, opposite to that taken by the author, which would give rise to a voltage in excess of the 2,000 value in a few microseconds.

If the capacitance of the truck to ground in the equivalent circuit given in Figure 1 can be considered as two series capacitances, that is, the capacitance of the truck to the roadway surface, which must be regarded as a conductive layer, and the roadbed as the dielectric of the second capacitance, this will reduce the effective capacity of the tank truck to ground according to the values of the series capacitances.

Here, in effect, would be three capacitances in series. After the grounding wire is connected, the potential on each capacitance would be inversely proportional to the value of the capacitance. If the capacitance of the element comprising the tires, roadbed, and so forth, is shunted by a resistor representing the leakage resistance, it then appears that the potential to ground on the tank would reach an initial maximum value when the tank is connected to the truck and would probably decrease as the current leaks off the roadway surface to the true ground instead of rising as indicated in Figure 2.

It appears evident to the writer that the curve in Figure 2 should start with the initial voltage on the tank as being the equilibrium value immediately after the ground wire is connected to the tank. Here the voltage would be equal to the voltage of the combined drops across the truck to roadway and the roadway to ground. The logarithmic rise or fall in potential of the tank to ground would depend on the assumptions made of the role played by the roadway as series capacitances. At any rate, the change in voltage to ground of the tank would be slight and would probably decrease instead of increase.

If the breakdown voltage of the insulation on the tank were 2,000 volts, is it not possible that initial breakdowns occurred without igniting the gasoline vapors? As the vapors were expelled from the vent pipe a flammable mixture could have accumulated gradually near the ground that was ignited by a subsequent discharge.

V. F. HANSON

(Electrochemicals department, E. I. Du Pont de Nemours and Company, Niagara Falls, N. Y.)

Terminal Corrections for Temperature Tests on Short Conductors

To the Editor:

We would like to make the following comments on the letter to the editor from Mr. W. N. Goodwin, Jr., "Terminal Corrections for Temperature Tests on Short Conductors," published in the January issue of *Electrical Engineering*, page 49.

Our main interest has been in temperature distribution along test samples for which the mid-point temperature rise is within one or two per cent of that which would occur with no terminal disturbance. Such conductors are usually short physically, but are correctly described by Mr. Goodwin as being long thermally. It is true that the long-line method is an approximation and that substantial errors occur when it is applied to sufficiently short conductors. We appreciate this clear-cut quantitative illustration, and hope that our previous letter (*EE, Nov. '42, p. 585*) did not seem to claim a too general validity.

In the calculation of thermally short conductors a practical difficulty appears which may not be obvious from reading Mr. Goodwin's paper, "The Compensated Thermocouple Ammeter," published in AIEE *Transactions*, volume 55, January section, pages 22–33, or from his letter. His equations cannot be directly applied to the interpretation of test data on thermally short conductors, for such data do not provide any direct means of measuring the over-all heat transfer coefficient, c, between the conductor and the surrounding medium. Therefore, the quantities θ_0, the temperature rise of the conductor if no heat were conducted away, and n, the thermal attenuation constant, cannot be evaluated.

This difficulty can be eliminated by evaluating θ_0 by the following method, applicable to a uniform conductor having equal temperature rises at the terminals, $T_1 = T_2 = T$. The linear heat conduction is then zero at the mid-point, and either half of the conductor can be treated as a short d-c line, open at the far end. Electrically, such a situation is expressed by

$$V_B = V_A \operatorname{sech} \alpha L \qquad (1)$$

where V_A and V_B are the sending and receiving end voltages, respectively, and αL is the hyperbolic angle subtended by the whole line. The corresponding thermal quantities are V_A, the temperature disturbance at the terminals caused by the terminals, and V_B, the temperature disturbance at the mid-point caused by the terminals. Then $V_A = (T - \theta_0)$ and $V_B = (\theta_c - \theta_0)$. Substituting in (1):

$$(\theta_c - \theta_0) = (T - \theta_0) \operatorname{sech} nL/2$$

This can be rearranged to read:

$$\theta_0 = \theta_c \frac{\cosh nL/2 - T}{\cosh nL/2 - 1}$$

In this equation θ_0 is still implicit in the right-hand-side, since $n = (w/akt_0)^{1/2}$. However, θ_c can be found by using θ_c instead of θ_0 in the initial evaluations of n, and then using the method of successive approximations. The expression converges fairly rapidly, and for the example of the two-foot length of 3/0 wire already considered, three substitutions give a result for θ_0 that is two per cent from the correct one. In this particular case the terminals cause a 28 per cent disturbance $(\theta_c - \theta_c)/\theta_0$ at the mid-point, whereas long-line computation indicates a disturbance of only seven per cent.

We wish to correct a proofreading slip in our previous letter (*EE, Nov. '42, p. 585*). The final paragraph should read ". . . If the temperature disturbance at the midpoint of a sample is to be limited to one per cent of that at the terminals, the minimum sample lengths range from about 4 feet for number 4 copper wire, to 12 feet for *750,000* circular mils conductor. . . . ."

FREDERICK BAUER (A '42)
JEROME J. TAYLOR (A '40)
(Detroit (Mich.) Edison Company)

Regulation and Load Division in Three-Phase Four-Wire Networks

To the Editor:

In the November 1941 issue of *Electrical Engineering* a letter to the editor written by the author on "An A-C Application of Hyperbolic Functions" appears on pages 563–4. Under conclusions it was stated: "The above method can be applied to a network with a concentrated load midway between blocks and also where the distance between blocks east and west is L and between blocks north and south in KL where K is any constant." The concentrated loads in north and south blocks likewise are assumed to be K times the concentrated loads in east and west blocks.

In this letter the author will present the theory for calculating current distribution and lowest voltage in a network with feeders staggered for case (*a*) no feeders tripped out; case (*b*) feeder 1 tripped out. The case for feeders not staggered is much simpler and therefore will be omitted. Finally a numerical example will be solved for cases (*a*) and (*b*). Nomenclature used is as follows:

- E = voltage at primary of transformer referred to secondary side
- E_s = nominal voltage at secondary side of transformer
- L = length in feet between blocks, east and west
- KL = length in feet between blocks, north and south (K is an integer)
- y = load admittance of secondary per unit length
- z = line impedance of secondary per unit length
- I_a = normal transformer current before feeder 1 is tripped
- Z_t = transformer impedance referred to secondary side

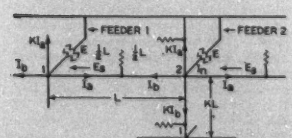

Figure 1. Case (a)—circuit 1 not tripped out

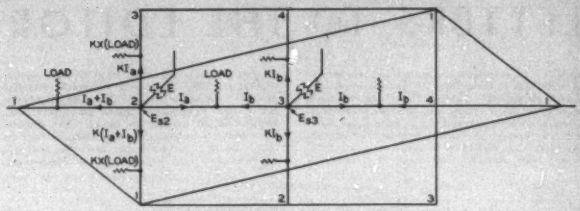

Figure 2. Case (b)—circuit 1 tripped out

Figure 1 shows total load I_a on transformer 2 with distances between blocks L and KL.

$$I_a = I_b;\quad KI_a = KI_b$$
$$I_a = I_a + I_b + KI_a + KI_b \text{ (or if } K=1)$$
$$I_a = 4I_a \qquad (1)$$

Now *

$$I_a = E_s yL/2 \text{ and } I_a = (E_s yL/2)2 + K(E_s yL/2)2 = E_s yL(K+1) \qquad (2)$$

$$I_a = (E_s yL/2)4 = 2E_s yL \quad \text{(if } K=1\text{) from equations 1 and 2} \qquad (3)$$

$$E_s = E - I_a Z_t \text{ (or if } K=1) \qquad (4)$$

$$E_{(\text{minimum})} = E_s - I_a zL/2 = E - I_a Z_t - I_a zL/2 \qquad (5)$$

Figure 2 shows symmetry on both sides of feeder 3 and can be truly represented by Figure 3 where one half of transformer number 3 feeds to the left with an equivalent impedance of $2Z_t$, and with a current

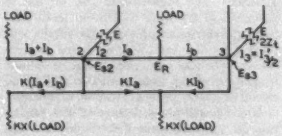

Figure 3

$I_3 = 1/2I_3'$ (I_3' = total current of transformer number 3).

As in case (*a*) (Figure 2)

$$I_a + I_b = E_{ss} yL \qquad (6)$$

(I_a and I_b are not numerically the I_a and I_b of case (*a*) and

$$K(I_a + I_b) = K(E_{ss} yL)$$

Now

$$I_3 = (I_a + I_b) + K(I_a + I_b) + I_a + KI_a = E_{ss} yL(K+1) + I_a(K+1) \text{ (see Figure 3)} \qquad (7)$$

Again $I_a = I_b + KI_b = I_b(K+1)$ (8)

Since E is constant $I_3 Z_t + I_a(zL/2) = I_2 Z_t + I_b(zL/2)$ (see Figure 3) (9)

Substituting I_2 of equation 7 and I_3 of equation 8 in equation 9

$$[E_{ss} yL(K+1) + I_a(K+1)]Z_t + I_a zL/2 = (K+1)I_b 2Z_t + I_b zL/2 \qquad (10)$$

or $I_a(K+1)Z_t + Z_t E_{ss} yL(K+1) + I_a zL/2 = I_b 2Z_t(K+1) + I_b zL/2$ (10a)

but $I_a = E_{ss} yL - I_b$ from (6). Substituting this value of I_a in (10a) and solving for I_b (assumed $E_{ss} = E_{rr} = E_s$)

$$I_b = E_s yL[(K+1)2z_t + zL/2]/3Z_t(K+1) + zL = E_s yL[4z_t + zL/2]/6z_t + zL \qquad (11)$$

(when $K=1$)

but $I_b = E_s yL - I_a$ from equation 6. Substituting this value of I_a in (10a) and solving for I_a

$$I_a = E_s yL(K+1)Z_t + zL/2/3z_t(K+1) + zL = E_s yL(2Z_t + zL/2)/6z_t + zL \qquad (12)$$

when $K=1$, from equations 7, 12, and 2

$$\frac{I_3}{I_a} = \frac{(K+1)4Z_t + 1.5zL}{3Z_t(K+1) + zL} = \frac{8Z_t + 1.5zL}{6z_t + zL} \quad \text{(when } K=1\text{)} \qquad (13)$$

from equations 8, 11, and 2

$$\frac{I_3'\ (=2I_3)}{I_a} = \frac{(K+1)4Z_t + zL}{3Z_t(K+1) + zL} = \frac{8Z_t + zL}{6Z_t + zL} \quad \text{(when } K=1\text{)} \qquad (14)$$

Assuming $E_{rr} = E_{ss} = E_s$ in above formulas greatly simplifies calculations and does not affect numerical results for I_3/I_a, I_3'/I_a', E_{ss}, and E_{rr} are accurately calculated later (see numerical problem).

Numerical problem:

L between blocks east and west = 250 feet
Network = 500,000-circular mil single conductor cable (approximately 4-inch spacing in duct)
Power factor = 0.9 lagging
Each transformer load = 450 kw (3-phase load)

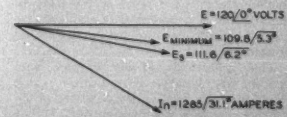

Figure 4. Vectorial values for case (a) using E as reference axis

E (referred to secondary) = 120 volts to neutral = $120\angle 0$ (reference axis Figure 4)

Y (admittance of line) = negligible

z (per foot) = 0.0000627$\angle$ 68.9° ohms

GE^3 = watts = 450,000/3 = 150,000/phase

$g = 150{,}000/120 \times 120 = 10.4$ mhos

g (each branch) = 10.4/4 = 2.6 mhos

therefore $Y_{(load)} = g/\cos\theta = 2.6/0.9 =$ 2.88$\angle$ 25.8° per 125 feet = 0.023$\angle$ 25.8° per foot

$i_{(transformer)} = 1.5$ per cent = $0.015 \times 120 = 1.8$ volts

$xi_{(transformer)} = 10$ per cent = $0.10 \times 120 = 12$ volts

but

$I_a = 150{,}000/0.9 \times 120 = 1{,}380\angle 25.8°$ approximate amperes

therefore

$r_t = 1.8/1{,}380 = 0.0013$ ohm

$x_t = 12/1{,}380 = 0.0087$ ohm

and

$$z_t = \sqrt{(0.0013)^2 + (0.0087)^2} = 0.0088\angle 81.5° \text{ ohms}$$

Case (*a*) circuit 1 not tripped out:

From equation 4

$E_a = E - I_a Z_t$

$E_a = 120 - (1{,}380)$ (approximately)$\angle 25.8° \times 0.0088 \cdot \angle 81.5) = 111.6\angle 5.3°$ volts

from equation 2

$I_a = E_a yL(K+1)$

(if $K = 1$)

$I_a = 111.6\angle 5.3 \times 0.023\angle 25.8° \times 2 \times 250 = 1{,}285\angle 31.1°$ amperes

$I_a = I_b = I_a/4 = 321 \cdot \angle 31.1°$ amperes (from equation 1)

Comment:

In solving for E_a, I_a is unknown but an approximate value 1,380$\angle$ 25.8° is used to get E_a; having obtained E_a an accurate $I_a = 1{,}285\angle 31.1°$ is obtained and this I_a could be used to obtain a more accurate E_a.

$E_{(minimum)} = E_a - I_a zL/2$ (equation 5)

$E_{(minimum)} = 111.6\angle 5.3° - 321.3\angle 31.1° \times (0.0000627\angle 68.9° \times 125)$

$E_{(minimum)} = 111.6\angle 5.3° - 2.52\angle 37.8° = 109.8\angle 6.2$

$$\text{Per cent regulation} = \frac{120 - 109.8}{109.8} = \frac{10.2}{109.5} = 9.3 \text{ per cent}$$

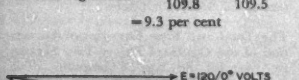

Figure 5. Vectorial values for case (b) using E as reference axis

Figure 4 shows these values vectorially, using E as the reference axis.

Case (*b*) circuit 1 tripped out:

From equation 13

$$\frac{I_2}{I_n} = \frac{8Z_t + 1.5zL}{6Z_t + zL} = \frac{(8 \times 0.0088\angle 81.5°) + (1.5 \times 0.0000627\angle 68.9° \times 250)}{(6 \times 0.0088\angle 81.5°) + (0.0000627\angle 68.9° \times 250)}$$

$\frac{I_2}{I_n} = \frac{0.0936\angle 78.4°}{0.0683\angle 78.4°} = 1.37 = 137$ per cent;

but $I_n = 1{,}285\angle 31.1°$

therefore,

$I_2 = 1.37 \times 1{,}285\angle 31.1° = 1{,}756\angle 31.1°$ amperes

from equation 14

$$\frac{I_2'}{I_n} = \frac{8Z_t + zL}{6Z_t + zL} = \frac{(8 \times 0.0088\angle 81.5°) + (0.0000627\angle 68.9° \times 250)}{(6 \times 0.0088\angle 81.5°) + (0.0000627\angle 68.9° \times 250)}$$

$\frac{I_2'}{I_n} = \frac{0.0859\angle 78.4°}{0.0683\angle 78.4°} = 1.256 = 125.6$ per cent;

but $I_n = 1{,}285\angle 31.1°$

Therefore

$I_2' = 1.256 \times 1{,}285\angle 31.1° = 1{,}615\angle 31.1°$ amperes; $I_3 = 807\angle 31.1°$ amperes

$I_4 = I_3$, by symmetry of Figure 2 = 1,758 $\angle$ 31.1° amperes

$I_1 = 0$ (circuit 1 tripped out)

$E_{a2} = E - I_2 2Z_t = 120\angle 0 - 807\angle 31.1° \times 2 \times 0.0088\angle 81.5° = 111.4\angle 5.8°$ volts

$E_{a3} = E - I_3 Z_t = 120\angle 0 - 1{,}765\angle 31.1° \times 0.0088\angle 81.5° = 110.6\angle 6.2°$ volts

From equation 12

$$I_a = \frac{E_{a3} yL(2Z_t + zL/2)}{6Z_t + zL}$$

$$I_a = \frac{110.6\angle 6.2° \times 0.023\angle 25.8° \times 250(2 \times 0.0088\angle 81.5° + 0.0000627\angle 68.9° \times 125)}{6 \times 0.0088\angle 81.5° + 0.0000627\angle 68.9° \times 250}$$

$I_a = \frac{15.93\angle 47.8°}{0.0683\angle 78.6} = 238\angle 30.8°$ amperes

$2(I_a + I_b) + 2I_a = I_3 = 1{,}756$; $I_a + I_b = 640$;

$I_b = 402$ (see Figure 2)

From equation 11

$$I_b = \frac{E_{a2} yL(4Z_t + zL/2)}{6Z_t + zL}$$

$$I_b = \frac{111.4\angle 5.8° \times 0.023\angle 25.8° \times 250(4 \times 0.0088\angle 8.15° + 0.0000627\angle 68.9° \times 125)}{6 \times 0.0088\angle 81.5° + 0.0000627\angle 68.9° \times 250}$$

$I_b = \frac{27.3\angle 50.2°}{0.0683\angle 78.6} = 403\angle 28.4°$ amperes (see Figure 2)

(All the previously mentioned calculations were made with slide rule with no interpolating of tables.)

$E_{minimum} (= E_R$ Figure 3$) = E_{a2} - zL/2I_b = 111.4\angle 5.8° - 0.0000627\angle 68.9° \times 125 \times 403\angle 28.4° = 108.4\angle 7.8$

$E_{minimum} (= E_R$ Figure 3$) = E_{a3} - zL/2I_a = 110.6\angle 6.2 - 0.0000627\angle 68.9° \times 125 \times 238\angle 30.8° = 108.4\angle 7.1°$

$$\text{Per cent regulation} = \frac{120 - 108.4}{108.4} = 10.7 \text{ per cent}$$

Figure 5 shows these values vectorially, using E as the reference axis.

CONCLUSIONS

(*a*) Transformers 2 and 4 are overloaded 37 per cent when circuit 1 is tripped out. Transformer 3 is overloaded 26 per cent when circuit 1 is tripped out.

(*b*) Minimum voltage drops from 109.5 to 108.4 volts when circuit 1 is tripped out.

(*c*) Total current before circuit 1 is tripped = 4 × 1,285 = 5,140 amperes. Total current after circuit 1 is tripped out = 0 + 1,756 + 1,615 + 1,756 = 5,127 amperes.

Total load 5,140 amperes drops to 5,127 amperes due to reduced voltage.

	Before Tripping (See Figure 1)	After Tripping (See Figure 2)
I_1	1,285	0
I_2	1,285	1,756
I_3	1,285	1,615
I_4	1,285	1,756
I_a	321	238
I_b	321	403
$I_a + I_b$	642	640

$I_a + I_b$, 642 amperes drops to 640 amperes due to reduced voltage.

Therefore one can conclude (*a*) that circuit 1 may be accidentally tripped at full load without serious overload or voltage drop for a short time, and (*b*) circuit 1 can be tripped daily at the substation during periods of light load and in this way reduce transformer-iron losses about 25 per cent. Similar calculations can be made for other arrangements of staggered circuits and when K is not unity. Loads need not be proportional to L and to KL.

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(Acting head, department of electrical engineering, Lehigh University, Bethlehem, Pa.)

Capacitance and Dissipation-Factor Correction

To the Editor:

In making measurements of capacitance and dissipation factor, it is sometimes necessary to make correction for the stray capacitance and leakage resistance of the instrument and leads. This correction, if worked out from fundamental considerations, is

lengthy and not adapted to slide-rule calculations. The following method was worked out when it was necessary to perform this calculation several times a day, and so far as known it has not been published. It assumes that the stray capacitance and leakage resistance can be regarded as a simple shunt across the unknown; also that the capacitance is measured in terms of the parallel network, or that it has been converted by the formula

$$C_{parallel} = \frac{C_{series}}{1+D^2}$$

Let the subscript T denote test values (C_T, D_T), the subscript o denote tare readings, and the subscript x denote the unknown. Then the capacitance can, of course, be corrected by simple subtraction: $C_x = C_T - C_o$. To correct the dissipation factor, compute the value of

$$D \frac{C_o}{C_x} (D_o - D_T)$$

D is a correction which, when algebraically subtracted from D_T, gives the value of D_x. It will be noted that this formula is well suited to slide-rule calculations or to mental estimates. It does not involve approximations or simplifying assumptions.

The derivation is as follows:

Assume that $D_x = D_T - D$

Then $D = D_T - D_x$

Now, $D \times C = \frac{1}{\omega} G$

where G is the conductance

and $\omega = 2\pi f$

and $G_x = G_T - G_o$

Therefore
$$D = \frac{G_T}{\omega C_T} - \frac{G_x}{\omega C_x} = \frac{1}{\omega}\left\{\frac{G_T}{C_T} - \frac{G_x}{C_x}\right\}$$
$$= \frac{1}{\omega}\left\{\frac{G_T}{C_T} - \frac{G_T - G_o}{C_T - C_o}\right\}$$
$$= \frac{1}{\omega}\left\{\frac{G_T C_T - G_T C_o - G_T C_T + G_o C_T}{C_T(C_T - C_o)}\right\}$$
$$= \frac{1}{\omega(C_T - C_o)}\left\{\frac{G_o C_T - G_T C_o}{C_T}\right\}$$
$$= \frac{1}{\omega C_x}\left\{G_o - \frac{G_T C_o}{C_T}\right\}$$
$$= \frac{C_o}{\omega C_x}\left\{\frac{G_o}{C_o} - \frac{G_T}{C_T}\right\}$$
$$= \frac{C_o}{C_x}\left\{\frac{G_o}{\omega C_o} - \frac{G_T}{\omega C_T}\right\}$$
$$= \frac{C_o}{C_x}\{D_o - D_T\}$$

GEORGE SHOMBERT, JR. (A '39)

(Assistant superintendent, test department, Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.)

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Patents and Industrial Progress. By George E. Folk. Harpers and Brothers, New York, N. Y., London, England, 1942. 387 pages, 8 1/2 by 5 3/4, $3.

The place of the patent in the industrial system of the United States is reviewed on the basis of material presented at the recent (1938 to 1941) hearings of the Temporary National Economic Committee. The testimony given before the committee is arranged to bring out the opposing cases presented by the Departments of Commerce and Justice. The separate reformatory recommendations and the final recommendations of the Committee are analyzed.

NAM Handbook on War Production. Compiled and Published by National Association of Manufacturers, Washington, D. C., New York, N. Y., San Francisco, Calif., August, 1942. 184 pages, charts, etc., 8 1/2 by 11 inches, paper, $1. (ESL).

This handbook for manufacturers is intended to bring together the information needed by those having war contracts or seeking them. How to go after a contract, how to sell to the Government, and the principles of cost determination under Government contracts are explained. The organization and functions of the War Production Board are described in detail, and the functions of the various agencies set forth. The priorities regulations are given in full, and there is a list of priorities orders, forms, and so forth.

Alternating-Current Machines. By A. F. Puchstein, T. C. Lloyd. 2d edition. John Wiley and Sons, Inc., New York, N. Y.; Chapman and Hall, London, England, 1942. 655 pages, illustrations, etc., 9 1/2 by 6 inches, cloth, $5.50. (ESL).

In dealing with the various types of a-c machines, each topic is treated approximately in the following order: construction; discussion of operating characteristics; calculation of operating characteristics from tests; discussions and analyses of various related phenomena. The revised edition has been brought up to date by the inclusion of new methods of analysis and recent standardization practices. As in the previous edition, only steady-state phenomena are covered with a few important exceptions.

The Vanderbilt Rubber Handbook. 8th edition. Edited by J. M. Ball. R. T. Vanderbilt Company, New York, N. Y., 1942. 464 pages, illustrations, etc., 8 1/2 by 5 1/2 inches, cloth, $5. (ESL).

This work brings together a large amount of technical information on rubber, especially on compounding for various purposes and on testing methods. Both dry rubber and latex are discussed.

PAMPHLETS • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

The Technical Book Publisher in Wartimes. By James S. Thompson. The New York Public Library, New York, N. Y., 1942. 24 pages, no charge.

Engineering in Our Early History. By Dugal C. Jackson. Reprinted from the Proceedings of the American Philosophical Society (volume 86, number 1), Lancaster, Pa., 1942. 51 pages.

Electric Power in Wartime. By Calman Winegarden. Bureau of Labor Statistics, United States Department of Labor, Washington, D. C., 1942. 17 pages.

Lesson of the Last World War. By James T. Shotwell. American Institute of Consulting Engineers, New York, N. Y., 1942. 46 pages.

How Management Can Integrate Negroes in War Industries. By John A. Davis. New York State War Council, 1942. 43 pages.

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TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Any discussion of these papers will appear in the June 1943 Supplement to Electrical Engineering—Transactions Section

Formulas for the Calculation of the Inductance of Linear Conductors of Structural Shape

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THE mechanical and electrical advantages stemming from the use of linear conductors of structural shape* are so marked that, at present, most busses for heavy current duty are constructed of such conductors. Thus, standard designs of single and polyphase busses utilize strap conductors of full rectangular cross section, tubular conductors of hollow rectangular cross section, or ventilated conductors of open hollow rectangular cross section—these last built up of two slightly separated channels or four slightly separated angles placed flange to flange, or of multiples of four thin strap conductors. Again, limited construction of a somewhat more specialized type of bus has resulted from Arnold's[1] discovery that minimum eddy-current losses are attained in a single-phase circuit if, of the conductors commercially available, the bus is constructed of two properly chosen channels placed back to back. Finally, the use, in shielded busses, of conductors of T and I cross section is not unknown.

Yet, despite the use of these various types of conductors, explicit formulas for calculating the inductance—and thence the reactive voltage drop, often the determining factor in the design of a heavy current bus—seemingly are available for only the first two types of conductors: those of full and those of hollow rectangular cross section. Papers by Arnold,[2] Carlson,[3] Darling,[4,5] Dwight,[6,7] Gray,[8] Grover,[9] Higgins,[10–12] Levy,[13] Maxwell,[14] Orlich,[15] Rosa,[16–19] Roth,[20] Schurig,[21] Silsbee,[22] Steidinger,[23] Sumec,[24] and others[25,26] contain formulas, curves, and tables that facilitate calculation of the inductance of a single-phase or of a polyphase bus comprised of identical conductors having parallel coplanar axes and parallel-sided full rectangular cross sections (if corresponding sides of two rectangular areas are parallel, but the areas are otherwise arbitrarily located, these areas are termed "parallel-sided"). And papers by Darling,[4,5] Dwight and Wang,[27] and Higgins,[10–12] contain formulas, curves and tables for calculating the inductance of a single-phase or of a polyphase bus comprised of identical conductors having parallel coplanar axes and parallel-sided hollow rectangular cross sections. But, seemingly, there have not been published explicit formulas for calculating the inductance of a bus comprised of full or hollow parallel-sided rectangular conductors arranged other than as just described; nor of a bus comprised of one of certain currently employed arrangements of linear conductors of L, T, [, or I cross section.

Such formulas are derived in this paper, it being assumed that the conductors are nonmagnetic, are of such length that end effects are negligible, are right-cornered, and carry currents uniformly distributed over their cross sections.

Of these four conditions, the first and second commonly are satisfied in practice. The third, however, though essential to tractable analysis, is not always true in practice. For example, strap conductors of full rectangular cross section are usually right-cornered, whereas conductors of hollow rectangular cross section commonly have rounded edges; again, channels built up of strap conductors are usually right-cornered, whereas channels drawn or rolled in one piece usually have rounded edges. However, error introduced by neglecting the rounded edges is usually small; moreover, where necessary the increase in inductance can be approximated by use of semiempirical formulas derived by Dwight and Wang.[27] Finally, neglect of skin and proximity effects is also essential to tractable analysis. However, the effect of these phenomena on the magnitude of the inductance is on the safe side, for the inductance decreases as the frequency is increased; moreover, at power frequencies and normal bus spacings this reduction in inductance is practically negligible (see, for example, the discussion following reference 27 or the experimental results published in reference 2).

If these four postulates are granted, derivation of the desired formulas, though lengthy, is not particularly difficult. First, the formula for the geometric mean distance between two *arbitrarily located* parallel-sided rectangular areas is derived by direct integration (sections I and II). Next, this formula and the fundamental theorem of geometric mean distance theory are conjoined to obtain formulas for the geometric mean distance between two arbitrary configurations comprised of parallel-sided rectangular areas; whence general formulas for the inductance of conductors of such cross sec-

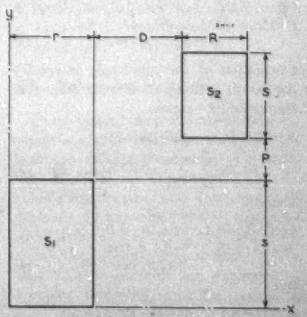

Figure 1

Paper 43-11, recommended by the AIEE committee on basic sciences for presentation at the AIEE national technical meeting, New York, N. Y., January 25–29, 1943. Manuscript submitted October 26, 1942; made available for printing November 16, 1942.

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* As conductors of full or annular circular cross section have been treated exhaustively elsewhere, they are not considered in this paper.

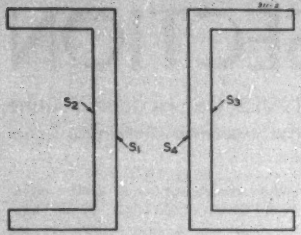

Figure 2

tion follow from application of well-known theory (sections III and IV). Finally, since the category just described embraces conductors of the type under discussion, distinct formulas for the inductance of specific types and arrangements of conductors can be deduced from these general formulas as desired (section V).

I. The Geometric Mean Distance Between Parallel-Sided Rectangles

The geometric mean distance D_{12} of a rectangular area S_1 from a second arbitrarily located rectangular area S_2 is defined by

$$S_1S_2 \log D_{12} = \int_{S_2}\int_{S_1} \log [|X-x|^2+|Y-y|^2]^{1/2} dS_1 dS_2 \quad (1)$$

(x, y) being the co-ordinates of a point in S_1 and (X, Y) those of a point in S_2.

If the rectangular areas are parallel-sided, are located as in Figure 1, and if P and D are *positive*, (the necessity and the significance of this restriction are discussed in section II), we have by equation 1

$$RSrs \log D_{12} = \int_{D+r}^{D+R+r}\int_{P+s}^{P+S+s}\int_0^Y\int_0^X \log [|Y-y|^2+|X-x|^2]^{1/2} dy dx dY dX \quad (2)$$

Evaluation of the quadruple integral—the details of integration are contained in the appendix—yields

$$RSrs \log D_{12} = -(25/12)RSrs - (1/24)\sum_{i=1}^{4}\sum_{j=1}^{4}(-1)^{i+j}K(A_i, B_j) \quad (3)$$

wherein

$$K(A_i, B_j) = (A_i^4-6A_i^2B_j^2+B_j^4)\times \log (A_i^2+B_j^2)^{1/2} - 4A_iB_j^3 \tan^{-1}(A_i/B_j) - 4A_i^3B_j \tan^{-1}(B_j/A_i) \quad (4)$$

and

$$A_1 = D+R+r;\ A_2 = D+R;\ A_3 = D;\ A_4 = D+r \quad (5)$$

$$B_1 = P+S+s;\ B_2 = P+S;\ B_3 = P;\ B_4 = P+s \quad (6)$$

Certain variants of equation 3 and of equation 4 are of value. Recalling that

$$\tan^{-1}(A_i/B_j) + \tan^{-1}(B_j/A_i) = \pi/2 \quad (7)$$

providing $A_i,\ B_j \geq 0$ we have by equations 4 and 7

$$K(A_i, B_j) = (A_i^4-6A_i^2B_j^2+B_j^4)\times \log (A_i^2+B_j^2)^{1/2} + 4A_iB_j(A_i^2-B_j^2)\tan^{-1}(A_i/B_j) - 2\pi A_i^3B_j$$
$$= (A_i^4-6A_i^2B_j^2+B_j^4)\times \log (A_i^2+B_j^2)^{1/2} + 4A_iB_j(B_j^2-A_i^2)\times \tan^{-1}(B_j/A_i) - 2\pi A_iBj^3 \quad (8)$$

As by equations 5 and 6

$$2\pi A_i^3\sum_{j=1}^{4}(-1)^jB^j = 2\pi B_j^3\sum_{i=1}^{4}(-1)^iA_i = 0 \quad (9)$$

providing *both P and D are positive* as postulated above, substitution of equation 8 in equation 3 yields

$$RSrs \log D_{12} = -(25/12)RSrs - (1/24)\sum_{i=1}^{4}\sum_{j=1}^{4}(-1)^{i+j}M(A_i, B_j) \quad (10)$$

wherein

$$M(A_i, B_j) = (A_i^4-6A_i^2B_j^2+B_j^4)\times \log (A_i^2+B_j^2)^{1/2} + 4A_iB_j(A_i^2-B_j^2)\times \tan^{-1}(A_i/B_j) \quad (11)$$

By virtue of the equivalent forms of the right-hand members of equation 8, and similarly those of equation 11, we obtain the useful identities

$$K(A_i, B_j) = K(B_j, A_i);\ M(A_i, B_j) = M(B_j, A_i) - 2\pi A_iB_j(B_j^2-A_i^2) \quad (12)$$

II. Generalization of P and D

The reason for the restriction, in section I, of P and D to positive values is evidenced by the following remarks on integration in the variable Y. If P and D are positive, we have $Y > y$; whence $(Y-y) \equiv |Y-y|$ and $d(Y-y)/dY \equiv d|Y-y|/dY$ over the domain of integration in Y; and integration in Y with either $(Y-y)$ or $|Y-y|$ in the integrand yields the same value. But if P and D can, separately, take on either positive *or* negative values, then over the range of integration in Y it may be that $(Y-y)$ takes on both positive and negative values. If so, $d|Y-y|/dY = 1$ if $Y > y$; but $d|Y-y|/dY = -1$ if $Y < y$; $|Y-y| = (Y-y)$ if $Y > y$, but $|Y-y| = -(Y-y)$ if $Y < y$; and integration with $(Y-y)$ in the integrand *may* yield a value different from that obtained with $|Y-y|$ in the integrand: for example,

$$\int_0^{2a}(Y-a)dY = 0, \text{ but } \int_0^{2a}|Y-a|dY = a^2;$$

contrariwise,

$$\int_0^{2a}|Y-a|^2dY = \int_0^{2a}(Y-a)^2dY = 2a^3/3$$

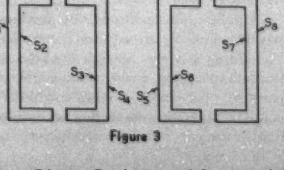

Figure 3

When with this point of analysis in mind the quadruple integral in the right-hand member of equation 2 is evaluated for each possible relative position of the two parallel-sided rectangular areas—the details of integration are discussed in the appendix—it is found that in each case equation 3 yet results *providing that in equation 3 A_i and B_j now indicate the following* (of which, obviously, equations 5 and 6 are special cases)

$$A_1 = |D+R+r|;\ A_2 = |D+R|;\ A_3 = |D|;\ A_4 = |D+r| \quad (13)$$

$$B_1 = |P+S+s|;\ B_2 = |P+S|;\ B_3 = |P|;\ B_4 = |P+s| \quad (14)$$

Further, as equation 7 is satisfied by these generalized values of A_i and B_j, equation 8 is likewise generally valid. Contrariwise, however, equations 10 and 11 are valid only if *both P and D are positive:* nevertheless, as this case frequently occurs in practice, these latter equations are most useful.

With the restriction on P and D thus removed, the foregoing equations afford the solutions to a host of electromagnetic problems (on the calculation of self-inductance and mutual inductance, reactance, line voltage drop, short-circuit bus stresses, and the like) that confront the engineer concerned with the design of single or polyphase busses composed of parallel linear conductors with axes not necessarily coplanar and with right cross sections comprised of arbitrary configurations of parallel-sided rectangles.

III. General Formulas for the Inductance and Reactance of Busses

Though solutions to problems of the type just mentioned can be obtained by direct use of the formulas derived in sections I and II, a considerable and very desirable simplification of the numerical

computation inherent to the actual design of a given bus can be effected if these formulas are conjoined with certain very general expressions to be derived by repeated use of the cardinal theorem of geometric mean-distance theory. This theorem states that:

If $S_1, S_2, \ldots, S_m$ are the components of a total area S; if $D_1, D_2, \ldots, D_m$ are their respective geometric mean distances from a second area S'; and if D is the geometric mean distance between S and S', then

$$SS' \log D = S_1S' \log D_1 + S_2S' \log D_2 + \ldots + S_mS' \log D_m \quad (15)$$

A direct corollary of this theorem is:

Let S' be comprised of component areas $S_1', S_2', \ldots, S_n'$. Then as by equation 15

$$S_1S' \log D_1 = S_1S_1' \log D_{11} + S_1S_2' \log D_{12} + \ldots + S_1S_n' \log D_{1n} \quad (16)$$

and as $S_2S' \log D_2, \ldots, S_mS' \log D_m$ can be expressed similarly, we have on substituting equation 16 and like forms in equation 15

$$SS' \log D = \sum_{i=1}^{m} (S_iS_1' \log D_{i1} + S_iS_2' \times \log D_{i2} + \ldots + S_iS_n' \log D_{in}) = \sum_{i=1}^{m} \sum_{j=1}^{n} S_iS_j \log D_{ij} \quad (17)$$

We note for later use that if each of the two cross sections is comprised of identical components numbered alike, $m=n$ and $S_{ij} \log D_{ij} = S_{ji} \log D_{ji}$.

Alternatively, if the components of S' are numbered from $m+1$ to $m+n$ instead of from 1 to n, we obtain from equation 17

$$SS' \log D = \sum_{i=1}^{m} \sum_{j=m+1}^{m+n} S_iS_j \log D_{ij} \quad (18)$$

For determining the self geometric mean distance of an area to itself equation 17 is preferable; for determining the geometric mean distance between two distinct areas equation 18 is preferable.

Granted the four postulates stated above, equations 15 to 18 inclusive facilitate derivation of convenient and compact expressions for the inductance of circuits comprised of parallel linear conductors of uniform but otherwise arbitrary cross section. Thus, invoking fundamental electromagnetic principles, if S_a and S_b are the cross sections of two conductors comprising a single-phase circuit carrying a current I, we have for the vector potential $A(X, Y)$ at a point (X, Y)

$$A = \text{constant} - 2\int\int_{S_a} w_a \log [|X-x|^2 + |Y-y|^2]^{1/2} dxdy - 2\int\int_{S_b} w_b \times \log [|X-x|^2 + |Y-y|^2]^{1/2} dxdy \quad (19)$$

wherein w_a and w_b are, respectively, the current densities in S_a and S_b, taken positive for current in one direction and negative for current in the other direction (hence, w_aw_b is a negative quantity, w_a^2 and w_b^2 positive quantities, and $I = w_aS_a = -w_bS_b$). The energy in the magnetic field associated with the circuit is

$$W = {}^1/_2 \int\int_{S_a} A(X, Y) w_a dXdY + {}^1/_2 \int\int_{S_b} A(X, Y) w_b dXdY \quad (20)$$

Substitution of equation 19 in equation 20, and then of equation 1 in the resulting expression yields

$$W = -(2w_aw_bS_aS_b \log D_{ab} + w_a^2S_a^2 \log D_{aa} + w_b^2S_b^2 \log D_{bb}) = I^2 \log (D_{ab}^2/D_{aa}D_{bb}) \quad (21)$$

Finally, recalling that $W = LI^2/2$, we have from equation 21

$$L = -(2/I^2)(2w_aw_bS_aS_b \log D_{ab} + w_a^2S_a^2 \times \log D_{aa} + w_b^2S_b^2 \log D_{bb}) = 2 \log D_{ab}^2/D_{aa}D_{bb} \quad (22)$$

If each of the two conductors is comprised of several component conductors connected in parallel, m comprising that with cross section S_a and n that with cross section S_b, substitution of appropriate forms of equations 17 and 18 in equation 22 yields

$$L = -(2/I^2)\Big[\sum_{i=1}^{m} \sum_{j=m+1}^{m+n} 2w_iw_jS_iS_j \log D_{ij} + \sum_{i=1}^{m} \sum_{j=1}^{m} w_iw_jS_iS_j \log D_{ij} + \sum_{i=m+1}^{m+n} \sum_{j=m+1}^{m+n} w_iw_jS_iS_j \log D_{ij}\Big] = -(2/I^2) \sum_{i=1}^{m+n} \sum_{j=1}^{m+n} w_iw_jS_iS_j \log D_{ij} \quad (23)$$

If we have two distinct circuits comprised of $p+q$ conductors *in toto*, p comprising one circuit and carrying current I_p, q comprising the other circuit and carrying current I_q, a similar analysis yields for the energy associated with the two circuits

$$W = -\sum_{i=1}^{p+q} \sum_{j=1}^{p+q} w_iw_jS_iS_j \log D_{ij} \quad (24)$$

Recalling that

$$W = MI_pI_q + L_pI_p^2/2 + L_qI_q^2/2 \quad (25)$$

substitution of equation 24 and of appropriate forms of equation 23 in equation 25 yields for the mutual inductance M

$$M = -(1/I_pI_q)\Big[\sum_{i=1}^{p+q} \sum_{j=1}^{p+q} w_iw_jS_iS_j \log D_{ij} - \sum_{i=1}^{p} \sum_{j=1}^{p} w_iw_jS_iS_j \log D_{ij} - \sum_{i=1}^{q} \sum_{j=1}^{q} w_iw_jS_iS_j \log D_{ij}\Big] \quad (26)$$

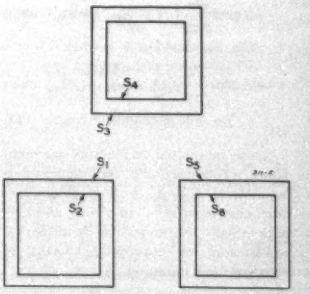

Figure 5

With regard to the physical quantities mentioned to this point, all units are in the absolute system: linear dimensions in centimeters, current I in abamperes, energy W in ergs per centimeter of line length, self inductance L and mutual inductance M in abhenrys per centimeter of line length. The 60-cycle reactance X in ohms per thousand feet of line length is obtained by multiplying a value of inductance by 11.48×10^{-3}.

IV. Polyphase Systems

In calculating the performances of polyphase systems it is necessary to know the reactance voltage drops on individual conductors. The well-known formulas for calculating the reactance drops are easily derived. In an n-phase system comprised of n distinct conductors, one conductor, say a, can be considered as carrying current I_a (the currents are expressed as complex numbers), and the remaining $n-1$ conductors can be considered as connected in parallel and carrying the

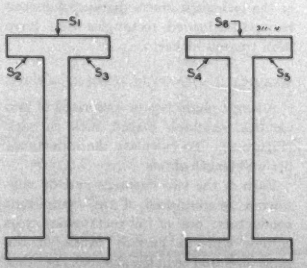

Figure 4

return current $-I_a=(I_b+I_c+\ \ \ +I_n)$. Accordingly, as the energy associated with conductor a is given by $W_a=\frac{1}{2}\int A w_a dS_a$, we obtain by selection of the appropriate terms from equation 22 that the associated inductance, $L_a=$ (reactance drop on conductor a)/$(2\pi f I_a)$, is

$$L_a=-(2/I_a^2)(w_a S_a \log D_{aa}+ w_a S_a \sum_{i=b}^{n} w_i S_i \log D_{ai})$$

$$=-2\sum_{i=a}^{n}(I_i/I_a)\log D_{ai} \text{ abhenrys per centimeter of conductor length} \quad (27)$$

By equation 27 the 60-cycle reactance is

$$X_a=-240\pi\sum_{i=a}^{n}(I_i/I_a)\log D_{ai} \text{ abohms per centimeter of conductor length}$$

$$=0.0528\sum_{i=a}^{n}(I_i/I_a)\ \log_{10}(1/D_{ai}) \text{ ohms per thousand feet of conductor length}$$

$$=0.2794\sum_{i=a}^{n}(I_i/I_a)\ \log_{10}(1/D_{ai}) \text{ ohms per mile of conductor length} \quad (28)$$

If the individual conductors are composite, a composed of a' conductors numbered from 1 to a', b of b' conductors numbered from $a'+1$ to $a'+b'$, and correspondingly for the others, we obtain by substitution of appropriate forms of equation 16 in equation 27

$$L_a=-(2/I_a^2)\left[\sum_{i=1}^{a'}\sum_{j=1}^{a'} w_i w_j S_i S_j \log D_{ij}+ \sum_{i=1}^{a'}\sum_{j=a'+1}^{a'+b'} w_i w_j S_i S_j \log D_{ij}+\ \ldots\ + \sum_{i=1}^{a'}\sum_{j=m'+1}^{m'+n'} w_i w_j S_i S_j \log D_{ij}\right]$$

$$=-(2/I_a^2)\left[\sum_{i=1}^{a'}\sum_{j=1}^{a'+\ \ldots\ +n'} w_i w_j S_i S_j \log D_{ij}\right]$$

abhenrys per centimeter length (29)

Corresponding formulas for the reactance are obvious from equation 28.

V. Some Illustrative Examples

The various parts of example 1 are advanced as corroborative of the fundamental formula given in equation 3, wherein A_i and B_i are as defined in equations 13 and 14. The succeeding examples are advanced as demonstrative of the application of the content of sections I to IV to the design of standard busses of various types.

EXAMPLE 1

Part A. The two rectangular areas of Figure 1 are to be considered as identical and superimposed. For this case: $r=R$; $s=S$; $D=-r$; $P=-s$. Then equations 13 and 14 yield: $A_1=A_3=r$; $A_2=A_4=0$; $B_1=B_3=s$; $B_2=B_4=0$. Whence, recalling that $\lim_{x\to 0} x^4 \log x=0$, substitution in equation 3 as indicated yields Maxwell's well-known formula for the geometric mean distance of a rectangular area to itself

$$\log D_{12}=\log(r^2+s^2)^{1/2}-(r^2/6s^2)\log[(r^2+s^2)/r^2]^{1/2}-(s^2/6r^2)\log[(r^2+s^2)/s^2]^{1/2}+(2s/3r)\tan^{-1}(r/s)+(2r/3s)\tan^{-1}(s/r)-25/12 \quad (30)$$

Part B. The two rectangular areas of Figure 1 are to be considered as identical squares ($R=S=r=s$), so located that $P=D=0$. Then equations 13 and 14 yield: $A_1=B_1=2r$; $A_2=B_2=A_4=B_4=r$; $A_3=B_3=0$. Whence, substitution in equation 3, as indicated, yields the known formula due to Rosa (reference 16, page 13)

$$\log D_{11}=\log r+3\log 2-(7/12)\log 5-4\tan^{-1}(1/2)+\pi-(25/12)$$
$$=\log r+0.34427+ \quad (31)$$

Part C. In similar fashion, if we take $r\neq R$, $s\neq S$, $D=D$, $P=-(s+S)/2$, we obtain Gray's well-known formula for the geometric mean distance between two dimensionally different, symmetrically located rectangles (reference 16, page 6); if we consider two identical squares ($R=S=r=s$), so located that $D=0$ and $P=P$, we obtain the known formula due to Rosa (reference 16, page 12); and if we take $r\neq R$, $s\neq S$, $D=-(r+R)/2$, $P=-(s+S)/2$, we obtain the writer's formula for the geometric mean distance between two symmetrically superimposed, dimensionally different rectangles (reference 11, page 1049). Accordingly, as verification of the analysis of sections I and II we have that equation 3 yields the known formulas for those special cases of the geometric mean distance between two parallel-sided rectangles that have been treated hitherto.

EXAMPLE 2

A single-phase bus is comprised of two identical channels placed back to back (Figure 2). To calculate the inductance per-unit length of bus:

Each of the two channels can be considered as comprised of two component conductors: one of full rectangular cross section wherein current exists in the same direction as in the channel, the other of smaller rectangular cross section having current in the opposite direction. Hence: $S_1=S_4$; $S_2=S_3$; $w_1=-w_2=w_3=-w_4=I/(S_1-S_2)$. Substituting in equation 23 yields

$$L=-(2/I^2)\sum_{i=1}^{4}\sum_{j=1}^{4} w_i w_j S_i S_j \log D_{ij} \text{ abenrys per centimeter of bus length} \quad (32)$$

Substituting in equation 32 as indicated and collecting terms, we have

$$L=-[4/(S_1-S_2)^2][S_1^2(\log D_{11}-\log D_{14})+S_2^2(\log D_{22}-\log D_{23})-2S_1S_2(\log D_{12}-\log D_{13})] \quad (33)$$

Corroboratively, if $S_2=S_3=0$ we have conductors of full rectangular cross section, and equation 33 reduces to the known formula $L=4\log(D_{14}/D_{11})$.

The six geometric mean distances in the right-hand member of equation 33 can be calculated from equation 3. Commonly, though, the value of the self geometric mean distance of a rectangle or of the geometric mean distance between two rectangles, symmetrically and externally located relative to one another, can be obtained—and usually more quickly than by calculation—from tables contained in certain of the references, especially reference 9. For other than this restricted class, though, equation 3 must be used perforce.

EXAMPLE 3

A single-phase bus is comprised of two identical open hollow rectangular conductors, each conductor consisting of two slightly separated channels placed flange to flange (Figure 3). To calculate the inductance per-unit length of bus:

Each of the two conductors can be considered as comprised of four component conductors: two of rectangular cross section wherein current exists in the same direction as in the split conductor; the remaining two of smaller rectangular cross section having current in the opposite direction. Hence: $S_1=S_4=S_5=S_8$; $S_2=S_3=S_6=S_7$; $w_1=-w_2=-w_3=w_4=-w_5=w_6=w_7=-w_8=I/2(S_1-S_2)$. By equation 23 the inductance of the bus is

$$L=-(2/I^2)\sum_{i=1}^{8}\sum_{j=1}^{8} w_i w_j S_i S_j \log D_{ij} \text{ abhenrys per centimeter of bus length} \quad (34)$$

Substituting in equation 34 as indicated and collecting terms yields

$$L=-[1/(S_1-S_2)^2][S^2(2\log D_{11}+2\log D_{14}-2\log D_{18}-\log D_{44})+S_2^2(2\log D_{22}+2\log D_{23}-2\log D_{28}-\log D_{27}-\log D_{32})-2S_1S_2(2\log D_{12}+2\log D_{13}-2\log D_{16}-\log D_{17}-\log D_{42})]$$
abhenrys per centimeter of bus length (35)

EXAMPLE 4

A single-phase line is comprised of two identical conductors of I cross section (Figure 4). To calculate the inductance per unit of bus length:

Each of the two conductors can be considered as comprised of three component conductors: one of rectangular cross section wherein current exists in the same direction as in the conductors of I cross section, the remaining two of smaller rectangular cross section having current in the opposite direction. Hence: $S_1 = S_4$; $S_2 = S_3 = S_4 = S_5$; $w_1 = -w_2 = -w_3 = w_4 = w_5 = -w_6 = I/(S_1 - 2S_2)$. By equation 23 the inductance of the bus is

$$L = -(2/I^2) \sum_{i=1}^{6} \sum_{j=1}^{6} w_i w_j S_i S_j \log D_{ij}$$

abhenrys per centimeter of bus length (36)

Substituting in equation 36 as indicated and collecting terms yields

$$L = -[4(S_1 - 2S_2)^2][S_1^2(\log D_{11} - \log D_{14}) + S_2^2(2 \log D_{22} + 2 \log D_{23} - 2 \log D_{24} - \log D_{25} - \log D_{26}) - 2S_1S_2(2 \log D_{12} - \log D_{14} - \log D_{15})]$$ abhenrys per centimeter of bus length (37)

EXAMPLE 5

A three-phase line is comprised of three equilaterally spaced rectangular tubular conductors (Figure 5). To calculate the inductance associated with one conductor, say a:

Each rectangular tubular conductor can be considered as comprised of two component conductors: one of rectangular cross section wherein current exists in the same direction as in the tubular conductors, the other of smaller rectangular cross section having current in the opposite direction. Hence: $S_1 = S_3 = S_5$; $S_2 = S_4 = S_6$; $w_1 = -w_2$; $w_3 = -w_4 = w_1\epsilon^{-j120^\circ}$; $w_5 = -w_6 = w_1\epsilon^{+j120^\circ}$. By equation 27 the associated inductance of the conductor a is

$$L_a = -(2/I_a^2) \sum_{i=1}^{3} \sum_{j=1}^{6} w_i w_j S_i S_j \log D_{ij}$$

abhenrys per centimeter of conductor length (38)

Noting that $w_1 = I_a/(S_1 - S_2)$, we obtain on substituting in equation 38 as indicated and collecting terms

$$L_a = -[2/(S_1 - S_2)^2][S_1^2(\log D_{11} + \epsilon^{-j120^\circ} \times \log D_{13} + \epsilon^{+j120^\circ} \log D_{15}) + S_2^2(\log D_{22} + \epsilon^{-j120^\circ} \log D_{24} + \epsilon^{+j120^\circ} \log D_{26}) + 2S_1S_2 (\log D_{12} + \epsilon^{-j120^\circ} \log D_{14} + \epsilon^{+j120^\circ} \log D_{16})]$$ (39)

Corroboratively, if $S_2 = S_4 = S_6 = 0$, the conductors are solid, and equation 39 reduces to the well-known expression

$$L_a = (2/I_c)[I_a \log (1/D_{aa}) + I_b \log (1/D_{ab}) + I_c \log (1/D_{ac})]$$ abhenrys per centimeter of conductor length (40)

Equation 40 also follows from equation 39 for the case of tubular conductors which are so thin that the cross sections can be considered as but comprised of four line segments. A specific treatment of this particular type of conductor and several numerical examples are to be found in a paper by Dwight and Wang:[27] they consider but square cross sections.

Appendix

Explicit evaluation of the quadruple integral

$$\int_{D+R}^{D+R+r} \int_{P+S}^{P+S+s} \int_0^r \int_0^s \log [|Y-y|^2 + |X-x|^2]^{1/2} dy dx dY dX$$

varies according as: (*i*) both P and D are positive; (*ii*) one or both of P and D is zero or is negative. In the first case, no logarithmic singularities are encountered in the course of evaluating the integral; whence integration can be effected directly through use of known tabulated integrals. In the second case, however, logarithmic singularities are encountered. These singularities necessitate repeated use of limits; whence the evaluation is considerably complicated. Additionally, as these singularities occur in a manner that varies with the relative position of the two rectangular areas of Figure 1, the process of integration must be modified for each possible distinct relative location; that is, for each possible combination of P and D mentioned in case (*ii*). Each of these various integrations has been effected; the very lengthy, purely formal analysis incident to evaluation is contained in a complementary paper to be published elsewhere. These integrations, however, differ only in mathematical detail from that for case (*i*), which follows. As mentioned, this case ($P, D > 0$) is the simplest to evaluate: even so, the easily reproduced, elementary analysis is so extensive and space filling that it is deemed advisable to present but the end result of successive integrations.

First

$$\int_0^s \log [(Y-y)^2 + (X-x)^2]^{1/2} dy = \left[-\frac{1}{2}(Y-y) \log [(Y-y)^2 + (X-x)^2] - (X-x) \tan^{-1} (Y-y)/(X-x) + (Y-y) \right]_{y=0}^{y=s}$$ (41)

From equation 41 we obtain

$$\int_0^r \int_0^s \log [(Y-y)^2 + (X-x)^2]^{1/2} dy dx = \left[\left[\frac{1}{2}(Y-y)(X-x) \log [(Y-y)^2 + (X-x)^2] - \frac{1}{2}[(Y-y)^2 - (X-x)^2] \times \tan^{-1}(Y-y)/(X-x) + \pi(Y-y)^2/2 - (Y-y)(X-x)/2 + (Y-y)x \right]_{y=0}^{y=s} \right]_{x=0}^{x=r}$$ (42)

From equation 42 we obtain

$$\int_{P+s}^{P+S+s} \int_0^r \int_0^s [\log (Y-y)^2 + (X-x)^2]^{1/2} dy dx dY = \left[\left[\left[\frac{1}{4}(Y-y)^2(X-x) - \frac{1}{12}(X-x)^3 \log [(Y-y)^2 + (X-x)^2] - [1/6(Y-y)^3 - 1/2(Y-y)(X-x)^2] \tan^{-1}(Y-y)/(X-x) + \pi(Y-y)^3/6 - \delta(Y-y)^3(X-x)/12 + (Y-y)^2 x/2 \right]_{y=0}^{y=s} \right]_{x=0}^{x=r} \right]_{y=P+s}^{y=P+S+s}$$ (43)

From equation 43 we obtain

$$\int_{D+r}^{D+R+r} \int_{P+s}^{P+S+s} \int_0^r \int_0^s \log [(Y-y)^2 + (X-x)^2]^{1/2} dy dx dY dX = \left[\left[\left[\left[-\frac{1}{48} \times [(Y-y)^4 - 6(Y-y)^2(X-x)^2 + (X-x)^4] \log [(Y-y)^2 + (X-x)^2] - \frac{1}{6}[(Y-y)^3(X-x) - (Y-y)(X-x)^3] \times \tan^{-1}(Y-y)/(X-x) - 13(Y-y)^2 \times (X-x)^2/48 + \pi X(Y-y)^3/6 + (Y-y)^2 X x/2 \right]_{y=0}^{y=s} \right]_{x=0}^{x=r} \right]_{y=P+s}^{y=P+S+s} \right]_{X=D+r}^{X=D+R+r}$$ (44)

Finally, substituting the limits in the order indicated and collecting terms, we obtain from equation 44 that

$$\int_{D+r}^{D+R+r} \int_{P+s}^{P+S+s} \int_0^r \int_0^s \log [(Y-y)^2 + (X-x)^2]^{1/2} dy dx dY dX = -(25/12) - (1/24) \sum_{i=1}^{4} \sum_{j=1}^{4} (-1)^{i+j} K(A_i, B_j)$$ (45)

wherein A_i, B_j, and $K(A_i, B_j)$ designate the quantities defined in equations 4, 5, and 6.

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Steady-State and Transient-Stability Analysis of Series Capacitors in Long Transmission Lines

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IN long-distance large-block power transmission, where is reactance compensation applicable? The complete answer to this question involves the weighing of compensated line performance against its costs, tempered with engineering judgment. This paper presents the results of an analysis made to determine basic performance data of compensated lines under steady-state and transient conditions. The data presented therefore allow the question to be partly answered and, it is believed, to a sufficient degree to permit certain general conclusions to be drawn. The system designer is thus provided with the fundamentally necessary data permitting him to proceed with an economic analysis for his particular case, where the cost factors are available. It is felt that in this field lies the value of these data. The costs of the various factors for a particular case can be weighed with the performance obtained by the same factors. The best design must necessarily be one where per cent line compensation, number of parallel circuits, generator short-circuit ratio, and number of intermediate switching stations are all used to their optimum degree for a given reliability of service. The number of factors which may be varied obviously depends upon whether compensation is to be used for increasing the power limits of a system already in operation or to be used as a factor in the design of a projected system.

The urgency of the times and the requirements the war effort is placing and will place on the transmission systems, and projected, coupled with the necessity of careful use of critical materials, emphasizes the importance and timeliness of the subject. The compensated line concept is not new, but the basic performance data presented are, and they should prove useful in helping to determine the expected gains of reactance compensation in projected and existing systems. A more complete analysis can be made for a particular system when it is necessary to determine in detail the effect of various operating conditions and arrangements peculiar to the system under consideration.

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General Conclusions

The data given are specifically performance data, showing what can be accomplished technically with compensated lines. A satisfactory excursion into the economic realms is outside the scope of this paper. The availability of certain materials during the present times—as well as during normal times—obviously will have its influence in the ultimate solution of a transmission problem.

1. The first and obvious conclusion is: Reactance compensation is an effective method for increasing the transient- and steady-state-stability limits of a transmission system.

2. Existing systems, composed of machines with average characteristics and lines as short as 150-175 miles—whose characteristics are fixed, because the machines are already installed—can materially increase their stability limits with acceptable margins by reactance compensation.

3. The relatively large gains available through the use of special generator characteristics, intermediate switching stations, high-speed switching and relaying indicate their fundamental usage in *projected systems* above 200 miles in length whether or not reactance compensation is used. The economic line-length threshold of reactance compensation (not determined in this paper) will obviously vary in projected systems as the relative costs of all factors change.

4. Reactance compensation appears to be an essential requirement for a-c transmission of economic blocks of power with lines above 300 miles in length.

5. Since reactance compensation provides an effective manner of increasing the stability limits above the original design values,

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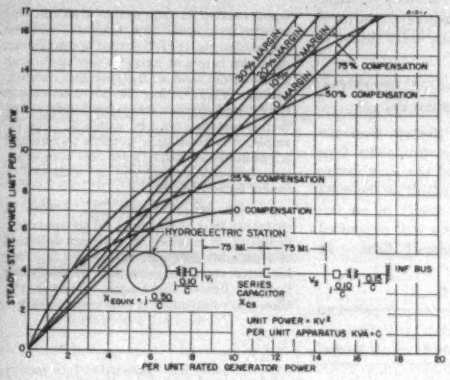


Figure 1. Steady-state stability limit of 150-mile line as a function of rating of hydroelectric generation at sending end

Transformer and low-voltage receiving-system capacitance increased in proportion to generator capacitance. Assumed generator power factor = 0.95. Held $V_1 = 1.0$ $V_2 = 0.95$

their possible use should tend to encourage a consideration of larger conductor sizes in order that the benefits from their use may be fully realized at the heavier system loadings.

6. The voltage rating of the series-capacitor equipment should be determined by—among other factors—the current during a stable-system transient oscillation, if maximum effectiveness is to be realized. This may mean a capacitor with higher than normal dielectric strength.

General Method of Analysis, Base Used, and System Studied

(*a*). The data presented in this paper, particularly those relating to transient stability, were obtained with the aid of an a-c network analyzer. The system was set up, with constants selected as described in the appendix and torque-angle curves obtained for the various conditions of fault on and off. Critical switching times were obtained by the application of the equal-area criterion.[1] Much of the steady-state work was done by well-known graphical methods.[2]

(*b*). It has been shown previously[3] that the loading of a transmission circuit varies with the square of the line voltage. For this reason it was considered convenient to make these studies on a kilovolt-ampere and kilowatt base which is given by the (kilovolts)² of the circuit under consideration Thus the data presented are entirely general and useful for any actual quantity of power and any value of voltage, except as the relation between these two quantities affects the per-unit power. The per-unit power transmitted on a (kilovolts)² base is given by the ratio

$$\frac{\text{kilowatts transmitted}}{(\text{transmission kilovolts})^2}$$

[For example, 150,000 kw on a (kilovolts)² base of (220)² gives a per-unit power of 3.1 and on a (161)² base gives a per-unit power of 5.0.]

(*c*). Based on a line surge impedance of 400 ohms, which is very nearly constant for all high-voltage lines, it has been shown[3] that the surge impedance or unity power-factor loading of such lines is 2.5 times the (kilovolts)²; hence this value of per-unit circuit loading on a (kilovolts)² base is the unity power-factor loading. Since at this loading the line reactive losses are entirely supplied by the charging kilovolt-amperes of the line itself, it is generally considered a good operating loading. With reactance compensation, part of the line reactive losses are supplied by the series capacitors; hence the loading which will consume the line-charging kilovolt-amperes is increased.

(*d*). A typical hydroelectric system was selected as the basis for this study, since long lines in general involve this type of system, and it is this type that generally has the more severe stability problems. A sketch is included with each curve showing the system arrangement applying for the particular case studied. Refer to the appendix for reactances and constants chosen.

(*e*). The stability analysis in general involved the selection of a generator kilovolt-ampere rating of C times the (kilovolts)². For each such rating selected, the rating of other terminal apparatus was made to match also by dividing its reactance on rating by the factor C, as discussed in Appendix II. In the steady-state-stability studies, summarized in Figures 1 to 3 inclusive, various values of system rating C were selected and the power limit for each determined. For convenience, the diagonal per cent margin line was included which intersects the power-limit curve at the per cent margin indicated. For the transient-stability studies, Figures 9 to 16 inclusive, various system ratings of C were selected and for each the critical switching time plotted, assuming the sending-end generator fully loaded before the fault.

Discussion of Results

I. Steady-State Stability, Single-Circuit Line—Figure 5

(*a*) *Results With Average Generator Characteristics*

1. *250 Miles.* Zero compensation permits a per-unit generator rating of 2.9 to transmit full load with 20 per cent margin. This value is substantiated by present practices.[5] In the future heavier loadings are technically feasible, and they may be justified by reactance compensation; for instance, 50 per cent compensation allows a rating of 5.1 with 20 per cent margin.

2. *300 Miles.* A per-unit rating of 2.5, generally referred to as the surge-impedance loading of an uncompensated line or the loading where the line supplies its own I^2x losses can be handled at this line length with:

0 compensation with 10 per cent margin
25 per cent compensation with 25 per cent margin

Thus, for this line length and this type of system, it appears that some compensation would be needed for steady-state stability for transmission of economical magnitudes of power depending upon the required margin.

3. *400 Miles.* A per-unit generator rating of only 2 can transmit full load with

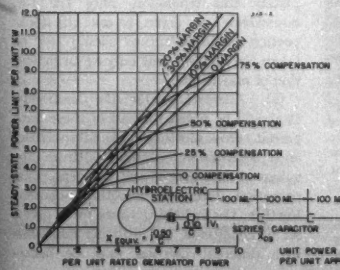


Figure 2 (left). Steady-state stability limit of 300-mile line as a function of rating of hydroelectric generation at sending end

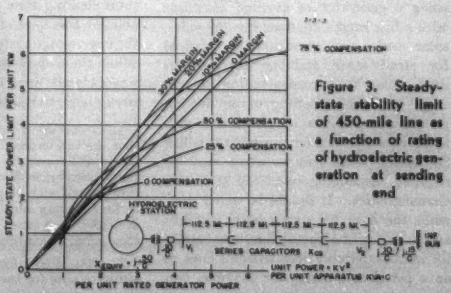


Figure 3. Steady-state stability limit of 450-mile line as a function of rating of hydroelectric generation at sending end

10 per cent margin a distance of 400 miles with no compensation. This indicates that series capacitors are undoubtedly required in lines of this length to transmit justifiable amounts of power.

(*b*) *Amount of Compensation.* There is an optimum value of compensation from a stability standpoint for a given line length. For a 300-mile line this value of compensation is about 75 per cent for the system constants chosen as shown in Figure 7. As the line length increases, this value also increases. Above this optimum value the over-all net impedance is predominantly resistance, so that voltage difference rather than phase angle tends to govern load flow. This is shown clearly in Figure 7 where the power which may be transmitted for compensation greater than optimum is larger for a line having five per cent voltage drop than for a line with flat regulation.

Table I

No. Switching Stations	Power Limits for Four Cycles Clearing—Two Lines (Per Cent Compensation)			
	0	25	50	75
0				
1				2.37
2			3.25	4.4
3		2.6	4.0	6.05
4	2.7			

(*c*) *Effect of Generator Short-Circuit Ratio.* See Figure 8. This factor was investigated for the 300-mile line operating at 20 per cent margin with the following results:

1. A compensation of 25 per cent will permit use of 1.2 short-circuit ratio in place of 2.0 with zero compensation, in transmitting output of a 2.5 per-unit generator.

2. A compensation of 50 per cent will permit use of short-circuit ratio of 1.3 in place of 2.5 with 25 per cent compensation in transmitting output of a 4.0 per-unit generator.

(*d*) *Summary, Steady-State Single-Circuit-Line Results.* It appears that, using a generator of average constants with a line length approaching 300 miles, some series compensation is required for steady-state stability to transmit more than that corresponding to the surge impedance loading of an uncompensated line, and so it follows that with loadings above this for line lengths below 300 miles, some compensation may be required, depending upon the generator characteristics. It should be noted that, while the data for steady-state stability are given for one circuit line, they apply for multiple circuit lines with all lines in on a per-circuit basis; for example, two such units studied may be operated in parallel with a steady-state limit of twice that given.

II. Transient Stability, Single-Circuit Line, Stub-Feeder Faults

(*a*). *Results With Average Generator Characteristics.* The stub-feeder type of fault was considered the most severe worth studying, since a fault on the main line would obviously result in an unavoidable loss which is a well recognized limitation of single-circuit lines. In evaluating these data, it is felt that a total clearing time of six cycles is reasonable, as this type of fault would occur in the low-voltage system at the receiver end. While these data were obtained, using a single-circuit line, they apply on a *per-circuit* basis to multicircuit lines.

Table II

	Read From Figure	At 230 Kv	At 287 Kv
Per-unit kilowatts transmitted		4.72	3.08
Per-unit kilowatts per circuit		2.36	1.52
Steady-state power limit per circuit	2		
0 compensation	2	2.7 (14.5 per cent margin)	2.1 (38 per cent margin)
25 per cent compensation	2	3.1 (31 per cent margin)	2.1*
50 per cent compensation	2	3.4 (46 per cent margin)	2.2*
75 per cent compensation	2	3.7 (57 per cent margin)	2.4*
			*Estimated
Fault-clearing time—cycles			
Two switching stations	15		
25 per cent compensation	Q		2.3
50 per cent compensation		0.8 ..	4.3
75 per cent compensation		3.55 ..	5.2
Three switching stations	16		
25 per cent compensation		0 (nearly) ..	3.7
50 per cent compensation		2.65 ..	5.0
75 per cent compensation		5.3 ..	6.0

1. *150 Miles.* It is found in the study that the full output of a per-unit generator rating of 2.8 can be transmitted with zero compensation, while a rating of 4.5 can be transmitted with 25 per cent compensation. If line loading above approximately 3 is desirable, then series capacitors will reasonably permit such operation in this area.

2. *300 Miles—Figure 10.* It is interesting to note for this case that 50 per cent compensation is required to transmit any reasonable power. For instance, with six cycles clearing, the full output of a maximum generator rating of 3 may be carried through a stub feeder fault with 50 per cent compensation. This loading is not particularly heavy, and so more compensation in a particular instance may be justified. For example, it is technically possible to transmit (eight kilovolts)^2 and 75 per cent compensation, but such loading will be tempered of course by economics.

3. *450 Miles—Figure 11.* With a switching time of six cycles, 66 per cent compensation is required to transmit full load of a per-unit generator rating of 2.5. This indicates that compensation is needed to justify a line of this length. Further, the allowable compensation falls within a rather narrow range, something between 65 per cent and 80 per cent (Figures 7 and 11).

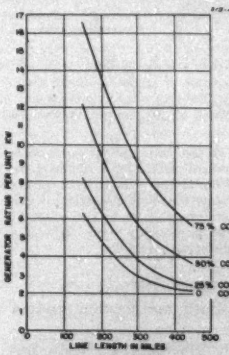


Figure 4. Data from Figures 1, 2, and 3 showing power limit in terms of generator rating with zero margin for various line lengths

Unit power = (kilovolts)^2

The stub-feeder faults as shown in Figure 11 indicate that the transient limit for small switching time is higher than the steady-state limit. These two boundaries define the results obtaining during the first swing and after an infinite number of swings, respectively. Because of the labor involved in determining completely this transition, only the two boundaries were given, so that the upper portion of these curves should not be taken too literally, but only as an indication of magnitude.

(*b*). *Interpretation for Other Conditions.* It should be noted that all of these data permit cross-plotting for interpolating and determining switching times for values of line length and per cent compensation different than those chosen. Further, the switching times for a given set of conditions, but utilizing machines with different inertias, may be deter-

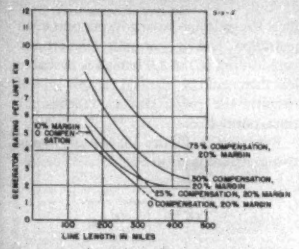


Figure 5. Data from Figures 1, 2, and 3 showing power limit in terms of generator rating with 10 per cent and 20 per cent margin for various line lengths

Unit power = (kilovolts)²

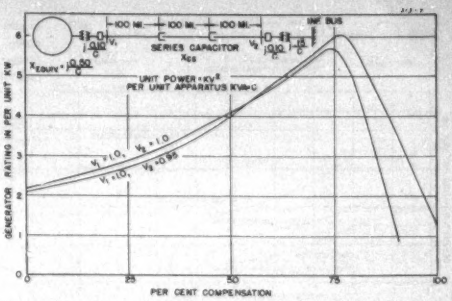


Figure 7. Effect of line voltage level on steady-state limit

Power limit in terms of generator rating with 20 per cent margin, for 300-mile line

mined by increasing the time by the factor $\sqrt{H/3}$, H being the new constant and 3 the value used in obtaining the data.

III. Steady-State Stability, Two Parallel Lines—Figure 12

For two-line circuits the worst fault through which the system may ride is a three-phase high-voltage fault at the sending end, resulting in loss of a line section. In view of this it is desirable to investigate the steady-state stability of the system with one line section out.

The multiplicity of the variables involved limited the scope of the investigation in general to a line length of 300 miles. This value was chosen since lengths in this area are being considered for future power transmission, and this, as well as previous studies, indicates that such lengths fall within a region where series capacitors should be given consideration.

The data summarized in Figure 12 show clearly how switching stations may be traded for compensation. It is interesting to note that 25 per cent compensation in the center of the line utilizing one switching station is equivalent to a large number of switching stations for steady-state stability with average generator constants. However, it must be remembered that the number of switching stations is dictated primarily by the transient-stability requirements.

IV. Transient Stability, Two Parallel Lines

In the analyses, data were obtained enabling the comparative effects of switching stations, per cent compensation, and clearing times to be studied. In evaluating the data, a total clearing time of four cycles will be used.

(a) Results With Average Generator Characteristics

1. *150 Miles—Figure 13.* Zero compensation allows a per-unit generator rating of 2.7 with no intermediate switching stations. As can be seen from Figure 13, probably more than the economic value of power can be transmitted with no compensation by the proper choice of switching stations. Economics obviously would determine whether switching stations, special generator characteristics, or compensation should be used to accomplish a given result.

2. *300 Miles.* The data given in Figures 14 through 17 for two parallel lines with 0–4 switching stations for various degrees of compensation are summarized in Table I for a clearing time of four cycles. Here the comparative effects of compensation and switching stations are readily seen. For example, 25 per cent compensation with three switching stations permits nearly the same per-unit generator rating as four switching stations with zero compensation.

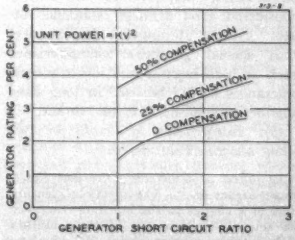


Figure 8. Effect of generator short-circuit ratio on steady-state limit

Power limit in terms of generator rating with 20 per cent margin, for 300-mile line. Assumed $x_{d(equiv)} = 0.7$/short-circuit ratio

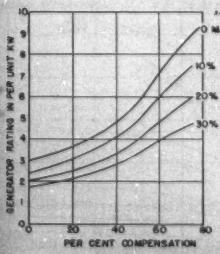


Figure 6. Data from Figure 2 showing effect of margin on required compensation, for a 300-mile line

Unit power = (kilovolts)². Steady-state power limit = generator rating (1 + margin)

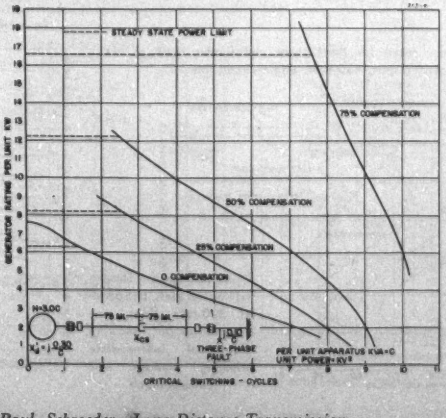


Figure 9. Switching-time curve for three-phase stub-feeder fault at low-voltage receiving end, 150-mile single-circuit line

Hydroelectric generating station carrying full rated load before fault

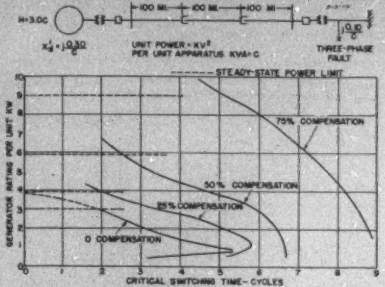


Figure 10. Switching-time curve for three-phase stub-feeder fault at low-voltage receiving end, 300-mile single-circuit line

Hydroelectric generating station carrying full rated load before fault

Similarly, two switching stations with 75 per cent compensation gives more margin than three switching stations with 50 per cent compensation.

Stability cannot be maintained for four cycle clearing time for the full output of any generator rating with the combination of conditions identified by the vacancies in Table I.

These loadings are well under the unity power-factor loadings, which are usually considered good average economic values. Hence, it appears fundamental that special generator characteristics such as high inertias and low transient reactances should be used in long lines whether compensation is used or not.

(*b*). *Interpretation of Results for Different Machine Characteristics*

1. *Effect of Generator Transient Reactance—Figure 18.* The effects on clearing time of a change in the machine reactance for several combinations of compensation and switching stations for a 300-mile line were studied. The results given in Figure 18 indicate that with a clearing time of four cycles, the full output of a per-unit generator rating of 2.5 can be transmitted with a 20 per cent transient reactance, two switching stations, and no compensation, as compared with a 30 per cent transient reactance, one switching station, and 50 per cent compensation.

2. *Effect of Generator Inertia.* Switching times given by these data may again be readily modified to apply to machines having inertia constants different from that used in the study, since they vary as the $\sqrt{H}$.

Refer to Figure 15 to see the effect of changing both H and x_d' in a particular instance.

V. Protective Equipment and Capacitor Voltage Ratings

In addition to normal load current through series capacitors, short-circuit currents and system swing currents after fault clearing must be considered.

Protective equipment will be required in general for short-circuiting the capacitors during the fault period. After the fault is removed the magnitude of the swing current may be such that it might be necessary to short-circuit the capacitors. Reference to Figure 19, which shows times normal swing currents which were measured during the single circuit—stub-feeder fault study, indicates that for a 150-mile line having 75 per cent compensation and a per-unit kilovolt-ampere loading (C) of 4.0 (which is probably less than could be justified for this type of circuit), the swing current reaches 2.7 times normal.

Referring to Figure 19, the maximum swing current is given by

$$I_S' = \frac{E_1 - E_2}{\frac{x_d' + x_1 + x_1 + x_3}{C} + x_1} = \frac{E_2}{\frac{x_3}{C} + x_1}$$

where

x_3 = total apparatus reactance on rating
x_1 = net line reactance
C = per-unit apparatus kilovolt-amperes

Since the per-unit normal capacitor current is C, the times normal swing current is

$$I_S = \frac{I_S'}{C} = \frac{E_2}{x_3 + x_1 C}$$

This shows that, as the kilovolt-amperes transmitted (C) increases, the maximum swing current decreases for a given net line reactance. Also, as the line reactance decreases holding C constant, the swing current increases, as would be expected.

For the system selected, the maximum swing current will not exceed 2.7 times normal because

(*a*). This value is obtained with a low value of C for the shortest line with the most compensation resulting in the lowest x_1.

(*b*). For greater values of C and x_1, the swing current will be less as shown above and by the curves, Figure 19.

These same per-unit values hold for multi-circuit lines with all circuits in. For the parallel line case with one line section

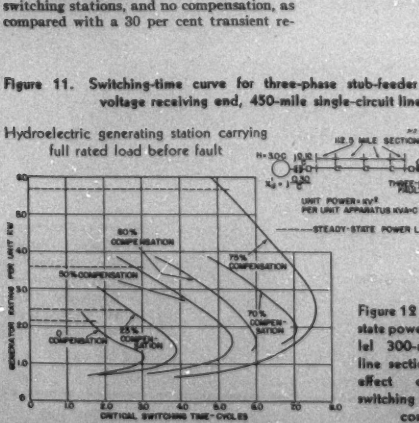


Figure 11. Switching-time curve for three-phase stub-feeder fault at low-voltage receiving end, 450-mile single-circuit line

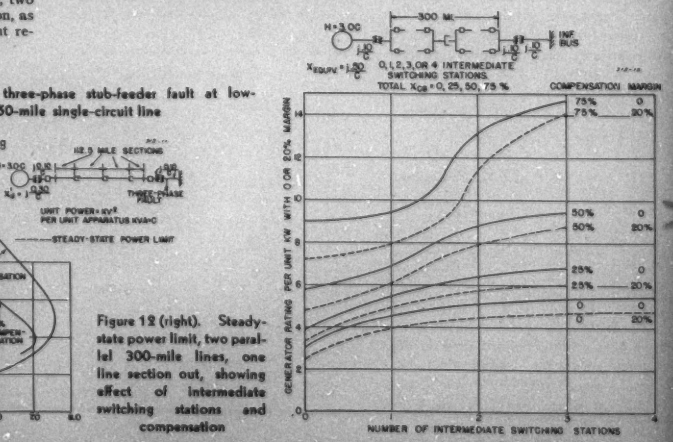


Figure 12 (right). Steady-state power limit, two parallel 300-mile lines, one line section out, showing effect of intermediate switching stations and compensation

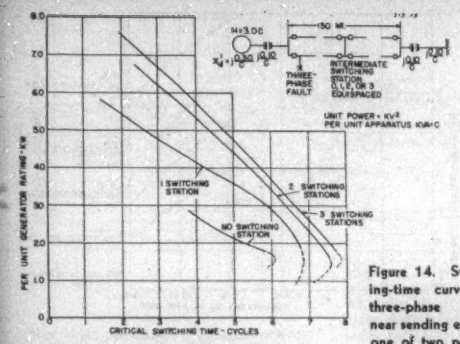


Figure 13. Switching-time curve for three-phase fault near sending end of one of two parallel 150-mile lines, for 0, 1, 2, and 3 intermediate switching stations

Fault results in tripping out of faulted line section. Hydroelectric generating station carrying full rated load before fault

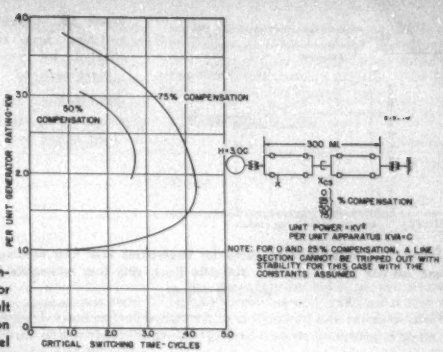

50% COMPENSATION
75% COMPENSATION
PER UNIT GENERATOR RATING=KW
CRITICAL SWITCHING TIME - CYCLES
300 MI.
H=3.00
% COMPENSATION
UNIT POWER = KV²
PER UNIT APPARATUS KVA=C
NOTE: FOR 0 AND 25% COMPENSATION, A LINE SECTION CANNOT BE TRIPPED OUT WITH STABILITY FOR THIS CASE WITH THE CONSTANTS ASSUMED

Figure 14. Switching-time curve for three-phase fault near sending end on one of two parallel 300-mile lines, with one intermediate switching station

Fault results in the tripping out of the faulted line section. Hydroelectric generating station carrying full rated load before fault

tripped out as a result of a fault clearing, the swing currents will be less than shown in Figure 19, because x_t is increased by virtue of the removed line section. The capacitor unit voltage rating should thus be determined by these current swings if maximum effectiveness is to be realized.

For certain fault locations the currents may be at times of such magnitude as to require the action of protective equipment. After the fault is removed, the capacitors should be placed back in service immediately, if maximum effect in maintaining stability is to be realized.

The effect of short-circuiting the capacitors instantaneously and then restoring them two cycles after the faulted line section is switched out is shown in Figure 15. This calculation involved the use of the equal area criterion as previously outlined.[4] The curves indicate that on this basis the most severe fault requiring the switching out of the capacitor is a little more severe than a three-phase fault on the sending end where the capacitors can be left in, or by-passed and immediately reinserted after the fault is removed with the same effect. It is thus shown that the effect of a two-cycle time delay in reinserting the capacitors is of such low magnitude that it could be neglected for the general study.

Machine Hunting and Abnormal Voltages

It is well known that hydroelectric generators not equipped with amortisseur windings connected to long lines experience hunting during light-load periods. It is also known that series capacitors magnify and encourage such hunting. A good analysis and bibliography of this phenomenon is given in reference 6. In this analysis it is shown that machines equipped with suitable amortisseur windings will not experience hunting when transmitting power over lines up to 300 miles (the extent of the study) in length and fully compensated. In view of these findings, and since a maximum of 75 per cent compensation is useful for stability reasons, it is felt that properly designed damper winding will prevent this difficulty.

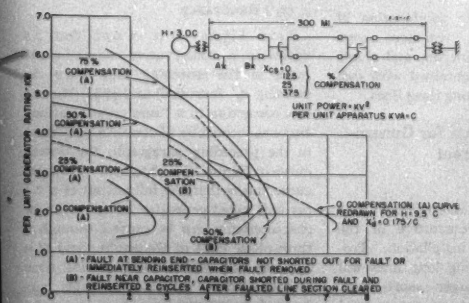
Reference 7 of the paper presents an analysis of possible abnormal voltages

Figure 15. Switching-time curve for three-phase fault near sending end on one of two parallel 300-mile lines, with two intermediate switching stations

Fault results in the tripping out of the faulted line section. Hydroelectric generating station carrying full rated load before fault

A—Fault at sending end—capacitors not short-circuited out for fault or immediately reinserted when fault removed

B—Fault near capacitor—capacitor short-circuited during fault and reinserted two cycles after faulted line section cleared


H=3.00
300 MI.
75% COMPENSATION (A)
50% COMPENSATION (A)
25% COMPENSATION (A)
0 COMPENSATION (A)
25% COMPENSATION (B)
50% COMPENSATION (B)
% COMPENSATION
UNIT POWER = KV²
PER UNIT APPARATUS KVA=C
0 COMPENSATION (A) CURVE REDRAWN FOR H=3.3 C AND X_d=0.175/C
(A) - FAULT AT SENDING END - CAPACITORS NOT SHORTED OUT FOR FAULT OR IMMEDIATELY REINSERTED WHEN FAULT REMOVED
(B) - FAULT NEAR CAPACITOR, CAPACITOR SHORTED DURING FAULT AND REINSERTED 2 CYCLES AFTER FAULTED LINE SECTION CLEARED
PER UNIT GENERATOR RATING=KW
CRITICAL SWITCHING TIME - CYCLES

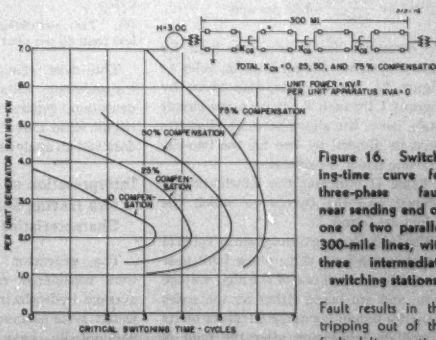


Figure 16. Switching-time curve for three-phase fault near sending end on one of two parallel 300-mile lines, with three intermediate switching stations

Fault results in the tripping out of the faulted line section. Hydroelectric generating station carrying full rated load before fault

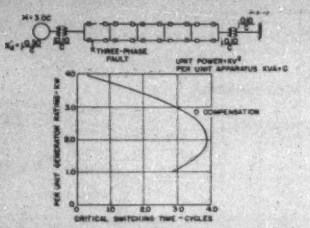
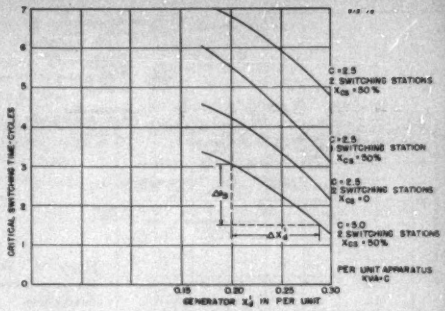


Figure 17. Switching-time curve for three-phase fault near sending end on one of two parallel 300-mile lines, with four intermediate switching stations

Fault results in the tripping out of the faulted line section. Hydroelectric generating station carrying full rated load before fault

Figure 18. Critical switching time as affected by transient reactance

300-mile line. Machine at full rated load before fault



occurring in long lines in general, and in lines having series capacitors in particular when an unloaded or lightly loaded transformer is left connected on the receiving end. These overvoltages become possibilities when low-side switching is used. Since high-side switching is generally necessary for stability, this should not present a serious problem. Attention is directed to this phenomenon so that it will receive just consideration in a particular instance.

Illustration of the Use of the Curves

Assume that it is desired to transmit the output of a 250,000-kw hydroelectric station a distance of 300 miles, over a two-circuit line, into a typical receiving system such as used in this study.

Consider two possible transmission voltages, 230 kv and 287 kv. The generator kilowatts are therefore

$$\text{At 230 kv } \frac{250{,}000}{(230)^2} = 4.72 \text{ per unit}$$

$$\text{At 287 kv } \frac{250{,}000}{(287)^2} = 3.03 \text{ per unit}$$

To determine the steady-state limit for such a system with all lines in, refer to Figure 2. Steady-state data given by Figures 1 through 8 are on a per circuit basis, hence the above per-unit kilowatts must be divided by two for the two-circuit line under consideration.

Table II indicates the information of interest and the curves on which the values are found.

The fault-clearing times given in Table II are of course for a three-phase fault near the sending end of one of the high-voltage lines, and are based either on the series capacitor remaining in the circuit or on its immediate reinsertion after the fault is removed. The *effect of increasing the* generator inertia may be determined by multiplying these times by $\sqrt{\text{per-unit generator } H/3.0}$. An estimate of the additional clearing time obtainable by the use of a lower generator transient reactance may be obtained from Figure 18, taking the Δt_c for a given $\Delta x_d'$, or conversely, finding the $\Delta x_d'$ required for a needed Δt_c.

It is seen that if four-cycle total clearing time is used, and the lines are designed for 230 kv, transient stability may be maintained, for example with:

(*a*). Two switching stations and 75 per cent compensation, and a per-unit generator H of 3.8 rather than 3.0, (or an x_d' of 0.28 instead of 0.30).

(*b*). Three switching stations, 50 per cent compensation, per unit $H = 6.85$ (or an x_d' of 0.23).

(*c*). Three switching stations, 75 per cent compensation.

If the lines are 287 kv, transient stability through a three-phase high-voltage sending-end fault may be maintained with

(*a*). Two switching stations, 25 per cent compensation, per unit $H = 9.1$ (or an x_d' of 0.20).

(*b*). Two switching stations and a little less than 50 per cent compensation.

The most economic combination of transmission voltage, reactance compensation, generator inertia, and short-circuit ratio may be obtained with cost data and an analysis along these lines.

Interpretation of Data for Generators Having Different Characteristics

The generator characteristics used were considered representative of the average hydroelectric installation. Projected systems involving long lines will undoubtedly have larger short-circuit ratios, lower transient reactances, and larger inertia constants than the average; hence a word on the interpretation of results for such cases will be given.

Consider a 300-mile two-circuit uncompensated line with two intermediate switching stations, with machine constants as follows:

X_d'	H constant
0.175	9.5—Boulder Dam Units[3]
0.30	3 —Used in this study

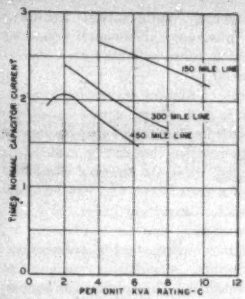
These are the constants of the 82,500-kw generators at Boulder Dam, and they represent a large variation from the average taken for this study.

(*a*) Correction for Inertia (H) Constant

The critical switching time for a given set of system conditions varies as the $\sqrt{H}$, and so for an H of 9.3, the critical switching time should be increased by $\sqrt{9.3/3} = 1.78$. Referring to Figure 15, for the case in question, the switching times of the curve for zero compensation should all be multiplied by 1.78 for a given generator rating.

(*b*). Correction for Transient (x_d') Reactance

From Figure 18 it is seen that 2.5 cycles is a conservative correction to make in the switching time when decreasing x_d' from 0.30 to 0.175. Making this correction to a "zero compensation" curve as located by H constant correction in the preceding paragraph, the dotted curve in Figure 18 is obtained. This new curve shows that the full output of a 2.4 per-unit rated generator having the new characteristics can be carried through a three-phase fault at the sending end of a 300-mile line with a total clearing time of four cycles. At 287.5 kv this corresponds to 280,000 kw, essentially agree-



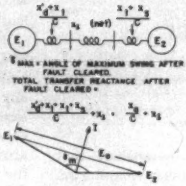


Figure 19. Maximum swing current with stability after clearing stub-feeder fault

Line 75 per cent compensated

ing with published calculated performance data for the 287.5-kv Boulder Dam–Los Angeles lines.[8]

Appendix I. Description of System Studied

A hydroelectric station, whose per-unit-kilovolt-ampere rating, called a factor C (see Appendix II), was varied, supplies power to an infinite bus through:

1. A step-up transformer bank of 0.10 per-unit reactance.
2. A transmission circuit of typical 60-cycle constants.
3. A step-down transformer bank of 0.10 per-unit reactance.
4. A receiving system having a steady-state per-unit reactance of 0.15 and a transient reactance of 0.10.

Constants selected for the generator in per unit on its rating were

$$x_{equiv} = 0.50 = \frac{0.70}{\text{short-circuit ratio}}$$

$$x_d' = 0.30$$

This corresponds to a short-circuit ratio of 1.4, which is representative of the average machine. The effects of both lower and higher short-circuit ratios were investigated. A generator power-factor rating of 0.95 was used as a nominal value for this type of application. A per-unit generator inertia or H constant of 3.0 was used, which is typical for a machine of normal short-circuit ratio. Since the critical switching times vary directly with $\sqrt{H}$, the effect of other values may be readily evaluated. The line constants selected as typical and nearly constant regardless of voltage for high-voltage 60-cycle lines, were

$$r + jx = 0.12 + j0.80 \text{ ohms per mile}$$
$$g + jb = 0 + j5.2 \times 10^{-6} \text{ mhos per mile}$$

The relationship between actual ohms and per-unit ohms on a given kilovolt-ampere base for a particular kilovolt is:

$$\text{per-unit ohms} = \frac{\text{actual ohms} \times \text{kilovolt-ampere base}}{(\text{kilovolts})^2\ 1{,}000}$$

Hence on the kilovolt-ampere base = (kilovolts)^2, used throughout this study

$$\text{per-unit ohms} = \frac{\text{actual ohms}}{1{,}000}$$

and therefore the line constants on the base selected varied only with line lengths. This was another convenience resulting from the use of this base.

Appendix II. A Note on the Factor C

A generator having a per-unit kilovolt-ampere rating of C as used in this study has a kilowatt rating of 0.95 C (kilovolts)^2, because a 0.95 power-factor machine was assumed throughout. For an equivalent reactance x_{equiv} of 0.50 on the kilovolt-ampere rating of C (kilovolts)^2 the reactance on the (kilovolts)^2 base is $0.50/C$. This follows from the relationship that

$$x_{equiv}\ (\text{on given base}) = x_{equiv}\ (\text{on rating}) \times \frac{\text{given base}}{\text{rating}}$$

Hence

$$x_{equiv}\ (\text{kv})^2\ \text{base} = x_{equiv}\ (\text{on rating})\ \frac{\text{kv}^2}{C(\text{kv})^2} = \frac{x_{equiv}\ (\text{on rating})}{C}$$

The same relation holds for the sending end and receiving end transformer and receiving system reactances, as indicated on the sketch accompanying each figure.

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A Useful Equivalent Circuit for a Five-Winding Transformer

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Synopsis: It has been indicated that there is a growing interest in the possibilities of multiwinding transformers with five windings. The lack of a suitable equivalent circuit for this type of transformer has retarded some of these engineering analyses. This paper presents a practical equivalent circuit, together with a development of the necessary formulas. Numerous mathematical manipulations have been omitted in the interest of brevity. Several of these manipulations are the key to the simplicity of the final working formulas. Examples show how the various equivalent-circuit parameters are evaluated. Factors affecting the voltage regulation of a five-winding transformer are brought out with the aid of an example in which two sources of supply are present. An objective of the analysis has been to keep the equivalent circuit suitable for the calculating board. Several precautions in this connection are discussed.

THE demand for electric power in greater quantities and with optimum continuity has increased the transmission engineers' interest in interconnected circuits and the multicircuit transformers associated therewith. Considerable has been published on three- and four-winding transformers.[1] This article enlarges the field to include a much more complicated unit, the five-winding transformer.

It should be emphasized that multicircuit transformers present many problems which cannot be solved by two-winding methods. These complications relate to leakage-impedance phenomena associated with the many fluxes illustrated in Figure 1. Among the more important characteristics affected by these phenomena are

(*a*). Voltage regulation.

(*b*). Load division between circuits.

(*c*). Parallel operation with other transformers.

(*d*). Efficiency.

(*e*). Short-circuit characteristics.

The interlinkage of the various leakage fluxes due to load currents in the different circuits affect the various voltages in complicated and sometimes unexpected ways. It is therefore necessary to have a clear conception of the leakage impedance relationships; otherwise the manipulation of the parameters may prove perplexing and unduly complicated.

Theory

The general theory of a five-winding transformer is no different from that with a lesser number of windings. Such a transformer consists of five separate windings that are mutually coupled by a single magnetic core, illustrated best as in Figure 1. This transformer can be analyzed in the conventional manner common to multicircuit transformers of a lesser number of windings, wherein the basic differential equations of voltage can be expressed as follows:

$$e_1 = r_1 i_1 + L_1 \frac{di_1}{dt} + M_{12} \frac{di_2}{dt} + M_{13} \frac{di_3}{dt} + M_{14} \frac{di_4}{dt} + M_{15} \frac{di_5}{dt}$$

$$e_2 = r_2 i_2 + L_2 \frac{di_2}{dt} + M_{21} \frac{di_1}{dt} + M_{23} \frac{di_3}{dt} + M_{24} \frac{di_4}{dt} + M_{25} \frac{di_5}{dt}$$

$$e_3 = r_3 i_3 + L_3 \frac{di_3}{dt} + M_{31} \frac{di_1}{dt} + M_{32} \frac{di_2}{dt} + M_{34} \frac{di_4}{dt} + M_{35} \frac{di_5}{dt}$$

$$e_4 = r_4 i_4 + L_4 \frac{di_4}{dt} + M_{41} \frac{di_1}{dt} + M_{42} \frac{di_2}{dt} + M_{43} \frac{di_3}{dt} + M_{45} \frac{di_5}{dt}$$

$$e_5 = r_5 i_5 + L_5 \frac{di_5}{dt} + M_{51} \frac{di_1}{dt} + M_{52} \frac{di_2}{dt} + M_{53} \frac{di_3}{dt} + M_{54} \frac{di_4}{dt}$$

where the subscripts refer to the windings involved, and

e = applied voltage
r = winding resistance
i = winding current
L = coefficient of self-inductance
M = coefficient of mutual inductance

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A rigorous mathematical treatment of the foregoing fundamental equations will lead to terms suitable for an equivalent circuit.

A true equivalent circuit for a transformer is one which cannot be distinguished from the actual transformer by any observations that can be made at its terminals. It is the *terminal* characteristics of a transformer and not the characteristics of some particular coil within the transformer that are of interest.

As in most practical transformer equivalent circuits, magnetizing current has been neglected. This results in an equivalent circuit of sufficient accuracy for most all power-circuit problems. The circuit contains components which represent winding resistance, self-inductance, and load or mutual impedance. Any winding can be used as the supply winding; in fact, more than one winding may be connected to a source of energy.

Properties of the Equivalent Circuit

It is a physical and mathematical necessity that a completely equivalent network have as many independent elements (or degrees of freedom) as the original system. The properties of a circuit for the problem at hand are:

1. The circuit must have five points of entry corresponding to the five windings of the transformer.

2. The circuit must have ten independent elements in order that the ten independent measurable impedances of the transformer may be simulated.

3. The circuit should be one that avoids excessive calculation. The impedances should be simple functions of the measurable transformer impedances obtained in commercial transformer production.

4. The circuit should be free from negative-impedance elements. Although this characteristic does not void the solution of any problem, it does complicate studies on a calculating board, as negative resistance cannot be easily provided. Moreover, a circuit with no negative reactance is desirable since it may be used on both the a-c and d-c calculating boards.

Upon designating the five windings of Figure 2, with the numbers 1, 2, 3, 4, and 5, the ten independent impedances which can be measured at the terminals of the transformer are:

$$\begin{array}{cccc} Z_{12} & Z_{13} & Z_{14} & Z_{15} \\ & Z_{23} & Z_{24} & Z_{25} \\ & & Z_{34} & Z_{35} \\ & & & Z_{45} \end{array}$$

Each of these impedances is measured by applying sufficient voltage to one of the windings, whose number appears in the subscript, to circulate a current in a short

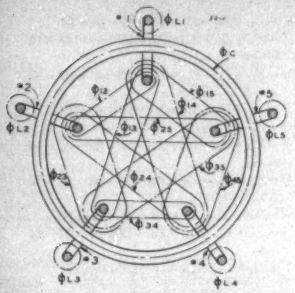

Figure 1. Flux linkages of a five-winding transformer

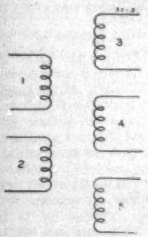

Figure 2. A simple five-winding transformer

circuit on the other winding, whose number appears in the subscript, its magnitude adjusted to the kilovolt-ampere base chosen. All other windings remain open-circuited.

The equivalent circuit used in this derivation of general formulas is that shown in Figure 3. Throughout the derivation of these general formulas, the loads indicated will not be considered.

Derivation of Formulas

Quantitative evaluation of the parameters for the five-winding transformer shown in Figure 3 can be obtained from these fundamental equalities:

$$Z_{12}=Z_1+Z_2+\frac{1}{\frac{1}{Z_6}+\frac{1}{Z_7+Z_8+Z_9+Z_{10}}} \quad (1)$$

$$Z_{13}=Z_1+Z_3+\frac{1}{\frac{1}{Z_6+Z_7}+\frac{1}{Z_8+Z_9+Z_{10}}} \quad (2)$$

$$Z_{14}=Z_1+Z_4+\frac{1}{\frac{1}{Z_6+Z_7+Z_8}+\frac{1}{Z_9+Z_{10}}} \quad (3)$$

$$Z_{15}=Z_1+Z_5+\frac{1}{\frac{1}{Z_6+Z_7+Z_8+Z_9}+\frac{1}{Z_{10}}} \quad (4)$$

$$Z_{23}=Z_2+Z_3+\frac{1}{\frac{1}{Z_7}+\frac{1}{Z_8+Z_9+Z_{10}}} \quad (5)$$

Table I. Mesh Currents for Example 2

Load On	Mesh Currents Due to Each Load Current				
	I_6	I_7	I_8	I_9	I_{10}
I_1...	47.49+j21.02	16.51−j69.02	16.51−j69.02	16.51−j69.02	16.51−j69.02
I_2...	60.20−j131.90	−119.01+j160.45	−60.20+j131.90	−60.20+j131.90	−60.20+j131.90
I_3...	217.30+j143.90	−202.30−j117.92	−202.30−j117.92	−217.30−j143.90	−217.30−j143.90
I_4...	15.69−j14.91	−2.52+j8.38	−2.52+j8.38	−2.52+j8.38	−15.69+j14.91
Total	340.68+j18.11	−307.32−j18.11	−248.51−j46.66	−263.51−j72.64	−276.68−j66.11

$$Z_{24}=Z_2+Z_4+\frac{1}{\frac{1}{Z_8}+\frac{1}{Z_6+Z_7+Z_9+Z_{10}}} \quad (6)$$

$$Z_{25}=Z_2+Z_5+\frac{1}{\frac{1}{Z_7+Z_8+Z_9}+\frac{1}{Z_6+Z_{10}}} \quad (7)$$

$$Z_{34}=Z_3+Z_4+\frac{1}{\frac{1}{Z_9}+\frac{1}{Z_6+Z_7+Z_8+Z_{10}}} \quad (8)$$

$$Z_{35}=Z_3+Z_5+\frac{1}{\frac{1}{Z_8+Z_9}+\frac{1}{Z_6+Z_7+Z_{10}}} \quad (9)$$

$$Z_{45}=Z_4+Z_5+\frac{1}{\frac{1}{Z_9}+\frac{1}{Z_6+Z_7+Z_8+Z_{10}}} \quad (10)$$

These equations can be simplified by successive steps and solved simultaneously resulting in the following ten expressions:

$$Z_6Z_7=(K-2Z_6)\frac{Z_t}{2} \quad (11)$$

$$Z_6Z_8=L\frac{Z_t}{2} \quad (12)$$

$$Z_6Z_9=M\frac{Z_t}{2} \quad (13)$$

$$Z_6Z_{10}=(N-2Z_6)\frac{Z_t}{2} \quad (14)$$

$$Z_7Z_8=(O-2Z_6)\frac{Z_t}{2} \quad (15)$$

$$Z_7Z_9=P\frac{Z_t}{2} \quad (16)$$

$$Z_7Z_{10}=Q\frac{Z_t}{2} \quad (17)$$

$$Z_8Z_9=(R-2Z_6)\frac{Z_t}{2} \quad (18)$$

$$Z_8Z_{10}=S\frac{Z_t}{2} \quad (19)$$

$$Z_9Z_{10}=(T-2Z_6)\frac{Z_t}{2} \quad (20)$$

in which

$$K=Z_{26}+Z_{12}-Z_{13} \quad (21)$$

$$L=Z_{13}+Z_{24}-Z_{14}-Z_{23} \quad (22)$$

$$M=Z_{14}+Z_{23}-Z_1-Z_{34} \quad (23)$$

$$N=Z_{12}+Z_{13}-Z_{23} \quad (24)$$

$$O=Z_{24}+Z_{26}-Z_{26} \quad (25)$$

$$P=Z_{24}+Z_{35}-Z_{34}-Z_{25} \quad (26)$$

$$Q=Z_{13}+Z_{25}-Z_{12}-Z_{35} \quad (27)$$

$$R=Z_{45}+Z_{34}-Z_{35} \quad (28)$$

$$S=Z_{14}+Z_{35}-Z_{13}-Z_{45} \quad (29)$$

$$T=Z_{45}+Z_{15}-Z_{14} \quad (30)$$

and

$$Z_t=Z_6+Z_7+Z_8+Z_9+Z_{10} \quad (31)$$

The links of the pentagonal mesh are evaluated by using the following algebraic relations in the second-degree equations 12, 13, 16, 17, and 19:

$$Z_7=aZ_6$$
$$Z_8=bZ_6$$
$$Z_9=cZ_6$$
$$Z_{10}=dZ_6$$

Equating various of the resulting expressions to the common quantity Z_6, these coefficients are obtained:

$$a=\frac{P}{M}$$

$$b=\frac{SP}{QM}$$

$$c=\frac{SP}{LQ}$$

$$d=\frac{S}{L}$$

Equations 11 to 20 inclusive are solved for various of the network parameters resulting in

$$Z_1=\frac{N}{2}-\frac{1}{Z_t}(Z_6Z_{10}) \quad (32)$$

$$Z_2=\frac{K}{2}-\frac{1}{Z_t}(Z_6Z_7) \quad (33)$$

$$Z_3=\frac{O}{2}-\frac{1}{Z_t}(Z_7Z_8) \quad (34)$$

Table A

Winding	Kilovolt-Ampere Base	Reactance Per Cent
1 to 2	20,000	14
1 to 3	20,000	20
1 to 4	5,000	12
1 to 5	5,000	15
2 to 3	20,000	16
2 to 4	5,000	10
2 to 5	5,000	11
3 to 4	5,000	8
3 to 5	5,000	8
4 to 5	5,000	6

$$Z_1=\frac{R}{2}-\frac{1}{Z_t}(Z_9Z_{10}) \tag{35}$$

$$Z_2=\frac{T}{2}-\frac{1}{Z_t}(Z_9Z_{10}) \tag{36}$$

$$Z_3=\frac{MQL}{2SP}+\frac{L}{2}\left(\frac{Q}{S}+1\right)+\frac{M}{2}\left(\frac{Q}{P}+1\right) \tag{37}$$

$$Z_7=\frac{P}{M}Z_3 \tag{38}$$

$$Z_8=\frac{SP}{QM}Z_3 \tag{39}$$

$$Z_9=\frac{SP}{QL}Z_3 \tag{40}$$

$$Z_{10}=\frac{S}{L}Z_3 \tag{41}$$

$$Z_t=Z_3+Z_7+Z_8+Z_9+Z_{10} \tag{31}$$

in which the constants are those previously defined.

Comments on Negative Impedance

No practical use can be made of the negative resistances or reactances of transformers as negative impedance by themselves. These negative impedances can be considered as mathematical fictions. They are virtual values. They reproduce faithfully the *terminal* characteristics of the transformer, but they cannot necessarily be applied to internal coils.

Negative resistance may appear in high-efficiency transformers in which the stray impedance losses become appreciable when compared with the low ohmic copper losses. This condition quite often occurs in three-winding transformers and is even more apparent in a five-winding transformer.

The total leakage reactance between a pair of windings cannot be negative, but there is no reason why the mutual effect between circuits for load currents may not be negative, depending on how the leakage field of one interacts with that of the other. In the circuits considered, the individual leakage impedances assigned to a circuit constitute mutual load impedance for the other circuits, and as such may be either positive or negative.

The total copper losses, including stray impedance losses, are correctly represented by the equivalent circuit, whatever the signs of its branches may be; but the simple equivalent circuit provides no means of distributing the losses within the transformer windings. Some of these losses are not in the windings at all, but in the clamps, core end plates, and tank, and therefore the conductor heating cannot be based on the losses of the equivalent circuit. However, the total impedance losses causing the heating of the oil are given by the equivalent circuit.

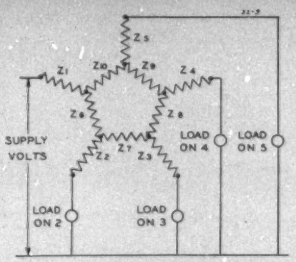

Figure 3. Five-winding transformer equivalent circuit

Examples

The foregoing theory can be applied to any five-winding transformer in a manner similar to that encountered in any electrical network. The only requirement is that certain data relating the actual circuits must be available either from measurements or from design calculations in order that the equivalent circuit may be set up. With the aid of the equations developed herein, each unknown can be evaluated singly. It is evident that all equations, depend upon determining the mesh impedances in the order Z_3, Z_7, Z_8, Z_9, and Z_{10}.

The application of these principles to two types of problems will be outlined in detail. Regardless of the degree of simplicity or complexity, the same precise rules must be followed. The importance of observance of the sign, positive or negative, accompanying each numerical value cannot be emphasized too strongly.

The first example demonstrates the use of this method of solution when only the reactance component of impedance is important. A second example treats resistance and reactance with equal importance, as is common when complex quantities represent the impedance units. Only a single-phase solution need be made for any balanced three-phase bank; however, if unlike transformers are involved, a solution for each phase must be made.

Example 1. Reactance Components Only. A five-winding transformer has the reactance between windings related to the kilovolt-ampere base indicated for each as shown in Table A. When all reactances are translated to a common kilovolt-ampere base, 20,000 in this case, the reactance values become those indicated in Table B. Then

$$K=Z_{23}+Z_{15}-Z_{12}=16+14-20=10$$
$$L=Z_{12}+Z_{34}-Z_{14}-Z_{23}=20+40-48-16=-4$$
$$M=Z_{14}+Z_{23}-Z_{\ldots}-Z_{34}=48+44-60-40=-8$$
$$N=Z_{12}+Z_{15}-Z_{23}=14+60-44=30$$
$$Q=Z_{34}+Z_{23}-Z_{24}=32+16-40=8$$
$$P=Z_{34}+Z_{25}-Z_{34}-Z_{23}=40+32-32-44=-4$$
$$Q=Z_{12}+Z_{25}-Z_{15}-Z_{23}=20+44-14-32=18$$
$$R=Z_{45}+Z_{34}-Z_{35}=24+32-32=24$$
$$S=Z_{14}+Z_{25}-Z_{15}-Z_{45}=48+32-20-24=36$$
$$T=Z_{45}+Z_{15}-Z_{14}=24+60-48=36$$

The mesh links are

$$Z_3=\frac{MQL}{2SP}+\frac{L}{2}\left(\frac{Q}{S}+1\right)+\frac{M}{2}\left(\frac{Q}{P}+1\right)$$
$$=\frac{(-8)\times18\times(-4)}{2\times36\times(-4)}+\frac{(-4)}{2}\left(\frac{18}{36}+1\right)+\frac{(-8)}{2}\left(\frac{18}{-4}+1\right)=9$$

$$Z_7=\frac{P}{M}\quad Z_7=\frac{(-4)}{(-8)}\times9=4.5$$

$$Z_8=\frac{SP}{QM}\quad Z_8=\frac{36\times(-4)}{18\times(-8)}\times9=9$$

$$Z_9=\frac{SP}{QL}\quad Z_9=\frac{36\times(-4)}{18\times(-4)}\times9=18$$

$$Z_{10}=\frac{S}{L}\quad Z_9=\frac{36}{(-4)}\times9=-81$$

$$Z_t=Z_3+Z_7+Z_8+Z_9+Z_{10}$$
$$=9+4.5+9+18-81=-40.5$$

and the branches are

$$Z_1=\frac{N}{2}-\frac{1}{Z_t}(Z_9Z_{10})$$
$$=\frac{30}{2}-\frac{1}{(-40.5)}(9\times-81)=-3$$

$$Z_2=\frac{K}{2}-\frac{1}{Z_t}(Z_9Z_7)$$
$$=\frac{10}{2}-\frac{1}{(-40.5)}(9\times4.5)=6$$

$$Z_3=\frac{O}{2}-\frac{1}{Z_t}(Z_7Z_8)$$
$$=\frac{8}{2}-\frac{1}{(-40.5)}(4.5\times9)=5$$

$$Z_4=\frac{R}{2}-\frac{1}{Z_t}(Z_8Z_9)$$
$$=\frac{24}{2}-\frac{1}{(-40.5)}(9\times18)=16$$

$$Z_5=\frac{T}{2}-\frac{1}{Z_t}(Z_9Z_{10})$$
$$=\frac{36}{2}-\frac{1}{(-40.5)}(18\times-81)=-18$$

Example 2. Determination of Current and Voltage Relations for a Five-Winding Transformer Under Load Conditions. A single-phase five-winding transformer has the characteristics shown in Table C and

Table B

Winding	Reactance Per Cent
1 to 2	14
1 to 3	20
1 to 4	48
1 to 5	60
2 to 3	16
2 to 4	40
2 to 5	44
3 to 4	32
3 to 5	32
4 to 5	24

impedance data given in Table D. The circuit diagram of this transformer is shown in Figure 2.

The following information about this transformer installation is required:

1. The equivalent circuit.

2. The load on winding 3 and its power factor when power is supplied from a transmission line to winding 2, maximum capacity 10,000 kva, and from a local generating station to winding 3. The load is on windings 1 and 5, and a synchronous condenser is on winding 4 for power-factor correction. The loads and their power factor are shown in Table E. In order to operate the transmission line connected to winding 2 at its optimum value, an overload of 1,500 kva is necessary on winding 4 from the synchronous condenser.

3. The voltage at each transformer terminal if it is desirable to maintain rated line voltage on winding 3, assuming load ratio control equipment is available to distribute the loads as given in 2.

Solution of 1. The equivalent circuit. The impedance when referred to a common base of kilovolt-amperes of 30,000 is:

$$Z_{12}=\left(\frac{50\times100}{10{,}000}+j20\right)3=1.5+j60$$

$$Z_{13}=\left(\frac{150\times100}{30{,}000}+j20\right)=0.5+j20$$

$$Z_{14}=\left(\frac{30\times100}{7{,}500}+j10\right)4=1.6+j40$$

$$Z_{15}=\left(\frac{15\times100}{5{,}000}+j15\right)6=1.8+j90$$

$$Z_{23}=\left(\frac{40\times100}{10{,}000}+j10\right)3=1.2+j30$$

$$Z_{24}=\left(\frac{52.5\times100}{7{,}500}+j5\right)4=2.8+j20$$

$$Z_{25}=\left(\frac{20\times100}{5{,}000}+j15\right)6=2.4+j90$$

Table C

Winding	Kilovolt-Amperes	Circuit Voltage
1	30,000	230,000 Wye
2	10,000	115,000 Wye
3	30,000	22,000 delta
4	7,500	13,800 delta
5	5,000	34,500 delta

$$Z_{34}=\left(\frac{45\times100}{7{,}500}+j10\right)4=2.4+j40$$

$$Z_{35}=\left(\frac{30\times100}{5{,}000}+j10\right)6=3.6+j60$$

$$Z_{45}=\left(\frac{25\times100}{5{,}000}+j5\right)6=3.0+j30$$

from which

$$K=Z_{23}+Z_{13}-Z_{12}=(1.2+j30)+(1.5+j60)-(0.5+j20)=2.2+j70$$

$$L=Z_{13}+Z_{34}-Z_{14}-Z_{23}=(0.5+j20)+(2.8+j20)-(1.6+j40)-(1.2+j30)=0.5-j30$$

$$M=Z_{14}+Z_{25}-Z_{15}-Z_{24}=(1.6+j40)+(2.4+j90)-(1.8+j90)-(2.8+j20)=-0.6+j20$$

$$N=Z_{12}+Z_{15}-Z_{25}=(1.5+j60)+(1.8+j90)-(2.4+j90)=0.9+j60$$

$$O=Z_{24}+Z_{23}-Z_{34}=(2.4+j40)+(1.2+j30)-(2.8+j20)=0.8+j50$$

$$P=Z_{24}+Z_{25}-Z_{34}-Z_{23}=(2.8+j20)+(3.6+j60)-(2.4+j40)-(2.4+j90)=1.6-j50$$

$$Q=Z_{13}+Z_{35}-Z_{12}-Z_{34}=(0.5+j20)+(2.4+j90)-(1.5+j60)-(3.6+j60)=-2.2-j10$$

$$R=Z_{45}+Z_{34}-Z_{35}=(3.0+j30)+(2.4+j40)-(3.6+j60)=1.8+j10$$

$$S=Z_{14}+Z_{45}-Z_{15}-Z_{45}=(1.6+j40)+(3.6+j60)-(0.5+j20)-(3.0+j30)=1.7+j50$$

$$T=Z_{45}+Z_{25}-Z_{24}=(3.0+j30)+(1.8+j90)-(1.6+j40)=3.2+j80$$

Substituting these values into the equations for the mesh impedances, 37 to 41, and 31, these result:

$$Z_4=\frac{MQL}{2SP}+\frac{L}{2}\left(\frac{Q}{S}+1\right)+\frac{M}{2}\left(\frac{Q}{P}+1\right)$$

$$=\frac{(-0.6+j20)(-2.2-j10)(0.5-j30)}{2(1.7+j50)(1.6-j50)}+\frac{(0.5-j30)}{2}\left(\frac{-2.2-j10}{1.7+j50}+1\right)+\frac{(-0.6+j20)}{2}\left(\frac{-2.2-j10}{1.6-j50}+1\right)$$

$$=0.697-j1.19$$

$$Z_7=\frac{P}{M}\quad Z_4=\frac{1.6-j50}{-0.6+j20}(0.697-j1.19)$$

$$=-1.749+j2.97$$

$$Z_8=\frac{SP}{QM}\quad Z_4=\frac{(1.6-j50)(1.7+j50)}{(-2.2-j10)(-0.6+j20)}\times(0.697-j1.19)=11.05-j12.75$$

$$Z_9=\frac{SP}{QL}\quad Z_4=\frac{(1.7+j50)(1.6-j50)}{(-2.2-j10)(0.5-j30)}\times(0.697-j1.19)=-7.48+j8.40$$

$$Z_{10}=\frac{S}{L}\quad Z_4=\frac{1.7+j50}{0.5-j30}(0.697-j1.19)$$

$$=-1.06+j2.04$$

$$Z_1=Z_3+Z_7+Z_8+Z_9+Z_{10}=(0.697-j1.19)+(-1.749+j2.97)+(11.05-j12.75)+(7.48+j8.40)+(-1.06+j2.04)$$

$$=1.46-j0.53.$$

It follows that the branch impedances from equations 32 to 36 inclusive are:

$$Z_1=\frac{N}{2}-\frac{1}{Z_t}(Z_9Z_{10})=\frac{0.9+j60}{2}-\frac{(0.697-j1.19)(-1.06+j2.04)}{(1.46-j0.53)}=0.03+j28.03$$

$$Z_2=\frac{K}{2}-\frac{1}{Z_t}(Z_8Z_7)=\frac{2.2+j70}{2}-\frac{(0.697-j1.19)(-1.749+j2.97)}{(1.46-j0.53)}$$

$$=0.61+j31.98$$

$$Z_3=\frac{O}{2}-\frac{1}{Z_t}(Z_7Z_8)=\frac{0.8+j50}{2}-\frac{(-1.749+j2.97)(11.05-j12.75)}{(1.46-j0.53)}$$

$$=1.28-j12.45$$

$$Z_4=\frac{R}{2}-\frac{1}{Z_t}(Z_8Z_9)=\frac{1.8+j10}{2}-\frac{(11.05-j12.75)(-7.48+j8.40)}{(1.46-j0.53)}$$

$$=27.43-j117.70$$

$$Z_5=\frac{T}{2}-\frac{1}{Z_t}(Z_9Z_{10})=\frac{3.2+j80}{2}-\frac{(-7.48+j8.40)(-1.06+j2.04)}{(1.46-j0.53)}$$

$$=1.87+j56.65$$

Solution of 2. The Power Supplied to Winding 3 and Its Power Factor When the Fluctuating Load Is Absorbed by the Generating Station on Winding 3. In large power transformers the effect of losses and reactance on input energy and power factor as compared with the output and its

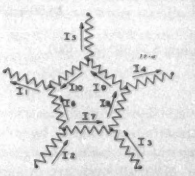

Figure 4. Assumed directions of currents for example 2

power factor is quite small, sufficiently so, to justify its omission in the interest of simplification.

The second source of power, that of winding 3, is regarded as a negative load.

Kilovolt-ampere load on winding 1
$=24{,}000\,(0.8-j0.6)=19{,}200-j14{,}400$
Kilovolt-ampere load on winding 2
$=-10{,}000\,(1.0+j0)=-10{,}000+j0$
Kilovolt-ampere load on winding 4
$=9{,}000\,(0.5+j0.866)=4{,}500+j7{,}794$
Kilovolt-ampere load on winding 5
$=4{,}500\,(0.9-j0.435)=3{,}950-j1{,}958$
Kilovolt-amperes supplied by winding 3
$=17{,}650-j8{,}564$
$=19{,}625$ kva at 89.9 per cent power factor

Table D

Winding	Kilovolt-Ampere Base	Copper Loss Kilowatts	Reactance Per Cent
1 to 2	10,000	50	20
1 to 3	30,000	150	20
1 to 4	7,500	30	10
1 to 5	5,000	15	15
2 to 3	10,000	40	10
2 to 4	7,500	52.5	5
2 to 5	5,000	20	15
3 to 4	7,500	45	10
3 to 5	5,000	30	10
4 to 5	5,000	25	5

Solution of 3. The Voltage at Each Transformer Line Terminal When It Is Desired to hold 22,000 Volts Across Winding 3 With the Local Generator. Since all values are expressed in terms of per cent with the exception of the loads, it is advantageous to convert all loads to a per cent basis using 30,000 kva as the reference. The per cent load on the windings is:

$$\text{On winding 1 } (19{,}200-j14{,}400)\frac{100}{30{,}000}=64-j48=I_1$$

$$\text{On winding 2 } (10{,}000+j0)\frac{100}{30{,}000}=33.33+j0=I_2$$

$$\text{On winding 3 } (17{,}650-j8{,}564)\frac{100}{30{,}000}=58.81-j28.55=I_3$$

$$\text{On winding 4 } (4{,}500+j7{,}794)\frac{100}{30{,}000}=15.00+j25.98=I_4$$

$$\text{On winding 5 } (3{,}950-j1{,}958)\frac{100}{30{,}000}=13.17-j6.53=I_5$$

The division of load by the various mesh circuits is arrived at by solving for the currents that exist, taking each load singly. After all loads are properly proportioned according to the rules of parallel circuits, the resultant current in each mesh link is found by a simultaneous superposition. Winding 2 is used as the source in all load-division computations. The direction of currents has been assumed as in Figure 4 in which the current in link 7 due to load on winding 1 is:

$$I_7=I_6=I_9=I_{10}=\frac{Z_6}{Z_t}I_1=\frac{0.697-j1.19}{1.46-j0.53}(64-j48)=16.51-j69.02$$

Also

$$I_6=I_1-I_7=(64-j48)-(16.51-j69.02)=47.49+j21.02$$

Table E

Winding	Kilovolt-Amperes	Per Cent
1	24,000	80 lagging
4	9,000	50 leading
5	4,500	90 lagging

Current in link 6 due to load on winding 3 is:

$$I_6=-I_{10}=-I_9=-I_8=\frac{Z_7}{Z_t}I_3=\frac{-1.749+j2.97}{1.46-j0.53}\times(-58.81+j28.55)=60.20-j131.90$$

Also

$$I_7=-I_6+I_3=(-58.81+j28.55)+(-60.20+j131.90)=-119.01+j160.45$$

Current in link 6 due to load on winding 4 is:

$$I_6=-I_{10}=-I_9=\frac{Z_7+Z_8}{Z_t}I_4=\frac{(-1.749+j2.97)+(11.05-j12.75)}{1.46-j0.53}\times(15.0+j25.98)=217.30+j143.90$$

Also

$$I_7=I_9=I_4-I_6=(15.0+j25.98)-(217.30+j143.90)=-202.30-j117.92$$

Current in link 7 due to load on winding 5 is:

$$I_7=I_8=I_9=\frac{Z_8+Z_{10}}{Z_t}I_5=\frac{(0.697-j1.19)+(-1.06+j2.04)}{1.46-j0.53}\times(13.17-j6.53)=-2.52+j8.38$$

Also

$$I_6=-I_{10}=I_8-I_7=(13.17-j6.53)-(-2.52+j8.38)=15.69-j14.91$$

The superposition of all currents is most conveniently handled in a table similar to Table I.

The per cent voltage at the terminals of any winding is determined by subtracting the per cent voltage drop through the circuit from the 100 per cent value assigned to the winding used as a reference.

The per cent voltage drop in the branches and links of the mesh is:

$$I_1Z_1=(64-j48)(0.03+j28.03)\frac{1}{100}=13.47+j17.93$$

$$I_2Z_2=(33.33+j0)(0.61+j31.98)\frac{1}{100}=0.20+j10.66$$

$$I_3Z_3=(58.81-j28.55)(1.28-j12.45)\frac{1}{100}=2.80-j7.69$$

$$I_4Z_4=(15.0+j25.98)(27.43-j117.70)\frac{1}{100}=34.71-j10.52$$

$$I_5Z_5=(13.17-j6.53)(1.87+j56.65)\frac{1}{100}=3.95+j7.34$$

$$I_6Z_6=(340.68+j18.11)(0.697-j1.19)\frac{1}{100}=2.59-j3.93$$

$$I_7Z_7=(-307.32-j18.11)(-1.749+j2.97)\frac{1}{100}=5.91-j8.81$$

$$I_8Z_8=(-248.51-j46.66)(11.05-j12.75)\frac{1}{100}=-33.42+j26.54$$

$$I_9Z_9=(-263.51-j72.64)(-7.48+j8.40)\frac{1}{100}=25.81-j16.70$$

$$I_{10}Z_{10}=(-276.68-j66.11)(-1.06+j2.04)\frac{1}{100}=4.28-j4.94$$

The voltage on the generator bus is held at 22,000 volts, which is our 100 per cent base and the point from which all voltages are calculated.

$$\text{Per cent } V_1=100-(I_6Z_6-I_7Z_7+I_8Z_8+I_1Z_1)=100-[(-2.80-j7.69)-(5.91-j8.81)+(2.59-j3.93)+(13.47+j17.93)]=92.65-j15.03$$

$$\text{and } V_1=230{,}000\sqrt{92.65^2+15.03^2}=216{,}000 \text{ volts}$$

$$\text{Per cent } V_2=100-(I_6Z_6-I_7Z_7-I_2Z_2)=100-[(-2.80-j7.69)-(5.91-j8.81)-(0.20+j10.66)]=108.51-j9.54$$

$$\text{and } V_2=115{,}000\sqrt{108.51^2+9.54^2}=125{,}400 \text{ volts}$$

$$\text{Per cent } V_4=100-(I_6Z_6+I_8Z_8+I_4Z_4)=100-[(-2.80-j7.69)+(-33.42+j26.54)+(34.71-j10.52)]=101.52-j8.33$$

$$\text{and } V_4=13{,}800\sqrt{101.52^2+8.33^2}=14{,}070 \text{ volts}$$

$$\text{Per cent } V_5=100-(I_6Z_6+I_8Z_8+I_9Z_9+I_5Z_5)=100-[(-2.80-j7.69)+(-33.42+j26.54)+(25.81-j16.70)+(3.95+j7.34)]=109.47-j9.49$$

$$\text{and } V_5=34{,}500\sqrt{109.47^2+9.49^2}=37{,}930 \text{ volts}$$

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Paired-Phase Bus Bars for Large Polyphase Currents

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THE design of efficient conductor systems for large alternating currents has always been a problem, and the problem is especially difficult with large low-voltage polyphase currents, such as are found in feeder distribution systems for industrial plants. Special conductor shapes and arrangements have been proposed in the past and have proved satisfactory for some applications, but all have had their limitations. A new method of arranging bus bars, named paired phasing, has now been developed and has been found to be superior to conventional arrangements for transmitting polyphase currents in the range of 1,000 amperes and above, at 600 volts and less.

The paired-phase arrangement is described in this paper in terms of enclosed bus-bar systems, as most of the experience in the use of the arrangement has been in that connection, but emphasis has been placed on the general characteristics of the arrangement rather than on this specific application. Therefore, the comparisons with conventional arrangements, the basic electrical and mathematical theory, and the construction and performance data will readily suggest the adaptability of paired phasing to other applications where efficient utilization of conductor materials and convenient structure are desired.

Only the three-phase version of the paired-phase arrangement is considered in this paper. It is shown in cross section in Figure 1. There are six conductors arranged in three separate and distinct pairs. The pairs are *a-b*, *b-c*, and *c-a*; that is, the two conductors in each close-spaced pair are connected to different phases. Each of the three phase currents is thus carried by two conductors in parallel. Wide flat bars placed face to face proved to have the most satisfactory conductor shape.

Summary

With the paired-phase arrangement, many of the difficulties associated with the transmission of large alternating currents are minimized. Nonuniform current density, including "skin effect" and "proximity effect," is greatly reduced. This results in low a-c energy losses which combines with effective heat dissipation to produce low and uniform temperature rise. Both resistance and reactance voltage drops are very small, and voltage drop is almost perfectly balanced. Furthermore, the dimensions that produce all these desirable electrical and thermal characteristics lend themselves to convenient structural designs wherein the problems of joining adjacent bus-bar lengths, making tap-offs, support against mechanical and short-circuit forces, and insulation are greatly simplified.

There are several specific features which particularly adapt the paired-phase arrangement to prefabricated enclosed bus-bar systems. Enclosure, of course, impedes heat dissipation, but the low heat generation minimizes this effect. Metallic or magnetic enclosures cause no additional losses and no increase in reactance. Structural designs are possible which facilitate erection in the field and the adaptation of standardized constructions to special installation conditions.

The paired-phase arrangement has several unique properties that distinguish it from previously known arrangements. Its low voltage drop and low losses depend largely upon close intrapair spacing, dimension *s* in Figure 1. The interpair spacing *d*, or different relative pair locations, as illustrated by the three variations of Figure 1, have no appreciable effect upon voltage drop and, therefore, may be varied to obtain low temperature rise and convenient structure. The balanced voltage drop of the paired-phase arrangement does not depend upon geometrical symmetry.

A peculiar inherent characteristic of the arrangement is that the currents in each close-spaced pair of bars are nearly equal and opposite, or somewhat similar to the currents in a single-phase transmission system, and this current division appears to be responsible for paired-phase performance. This single-phase approach also forms the basis of a simple method for calculating paired-phase performance.

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Paired-Phase and Conventional Arrangements Tested

The best way to appraise the performance of the paired-phase arrangements is by comparison with commonly used conventional arrangements, shown in Figure 2. In contrast to the paired-phase arrangement, the laminated arrangement has closely spaced bars connected to the same phase, while the interlaced arrangement has the bars evenly spaced and not grouped into distinct pairs.

A large amount of information has been published concerning open laminated bus bars where phases are well separated and no enclosures are present.[1,2] Most of this information is completely inapplicable to conventional enclosed bus-bar assemblies, because additional proximity-effect losses caused by interphase spacings of two or three inches, induced losses in metallic enclosures, and greatly restricted heat dissipation make performance much worse than commonly supposed. Some temperature-rise data for small-size enclosed bus bars and some reactance and resistance data for large-size bus bars in aluminum enclosures are available,[3] but to fully compare and contrast the performance of the paired-phase arrangement new data will be presented upon all of the arrangements shown in Figures 1 and 2.

Designs having two one-fourth- by four-inch round-edge copper bars per phase have been selected for presentation; this size represents medium rather than large current-carrying capacity and emphasizes the need for careful conductor design even in this size. The basic paired-phase theory applies equally well to all conductor sizes commonly used. In general, the relative performance of larger sizes of laminated bus bars is much poorer, while the relative performance of larger sizes of paired-phase and interlaced arrangements is roughly the same.

In order to simplify comparisons, a rectangular 14-gauge steel housing with a cross-section perimeter of 53 inches was used in all tests; the relative breadth and width were varied slightly to accommodate the various arrangements. A housing of this size represents standard practice for the wider-spaced arrangements, but is larger than would ordinarily

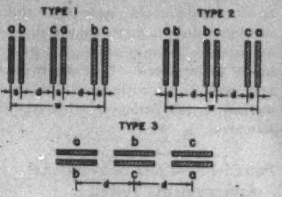


Figure 1. Three variations of the paired-phase bus-bar arrangement

s = intrapair spacing
d = interpair spacing
w = width

be used with the very compact arrangements having a small over-all width, w. Performance of commercial compact arrangements with a smaller housing would, therefore, usually be slightly inferior to that indicated.

The dimension s was kept constant at five-eighths inch during most paired-phase and laminated tests. Comparison of laminated performance with s equal one-half inch, the more conventional dimension, indicated a difference of small magnitude. An intrapair spacing of five-eighths inch represents a more than adequate spacing for practical paired-phase arrangements. The effect of variation of this dimension will, however, be discussed as the test results are analyzed.

All tests were made upon a 40-foot

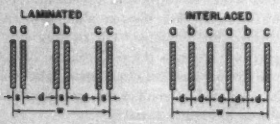


Figure 2. Conventional bus-bar arrangements

run, comprising four ten-foot sections, in order to minimize end effects. In each case, all bus bars were connected together at one end and low-voltage balanced three-phase 60-cycle current fed in the other end. Voltage measurements were made line to line at the feed-in end of the run to eliminate induced voltages in the potential leads. Power was measured by a special low-voltage wattmeter.

The point-to-point variation in current density in each bus bar was studied by insulated exploring wires cemented to the surfaces of the bars in the manner employed by a number of experimenters.[4-6] The exploring wire measurements also provided a means of analyzing the location of energy losses in greater detail than is possible with a wattmeter, which is suitable only for over-all averages. Each bar was equipped with 16 number

Figure 3. Typical test setup

28 wires, eight feet long, spaced at one-half inch intervals around the bar perimeter. The voltage induced in each wire, which is a measure of the current density adjacent to the wire, was measured by a rectangular co-ordinate a-c potentiometer. The total current in each bar was also measured with a magnetic potentiometer or Rogowski coil.[7]

Temperatures were measured by thermocouples. In all tests both the bus bars and housing were painted with a non-metallic paint to assure maximum and consistent heat radiation. All temperature rises given would be approximately 25 to 35 per cent higher if the bus bars were not painted and 50 to 70 per cent higher if neither housing nor bus bars were painted.

A portion of the research laboratory with a typical test setup is shown in Figure 3. One housing section has been removed so that the interior construction may be seen.

Voltage Drop, Temperature Rise, and Energy Losses

Relative voltage drops and temperature rises are given in Figure 4. Since the voltage drop is unbalanced to some extent in all arrangements, both the maximum line-to-line impedance drop and the minimum line-to-line impedance drop are plotted, with the area between shaded, so that the relative amount of unbalance may be seen. These values are plotted against the over-all width of the bus-bar assembly, w, for all of the vertical-bar arrangements, but it is not intended that comparisons be made only for equal over-all widths. This dimension has no direct significance for the paired-phase type-3 arrangement, but impedance drops and temperature rise for this arrangement are plotted to the same scales so that appraisals may be made. For all arrangements the maximum temperature rise decreases for increased spacings. In the case of the laminated and interlaced arrangements, increased spacing causes both increased voltage drop and increased voltage-drop unbalance; in the paired-phase arrangements increased interpair spacing causes substantially no change in voltage drop but provides better voltage-drop balance.

Impedance drops are separated into average reactance and resistance components in Figures 5 and 6, respectively. The reactance curves in particular show the independence of paired-phase characteristics upon relative pair position. The resistance curves show that both the paired-phase and interlaced arrangements have low average a-c resistance. This factor will be considered in more detail later in connection with an analysis of energy losses. The effect of intrapair spacing upon paired-phase reactance may be seen in Figure 7. This curve is actually for the type-3 arrangement but applies approximately to any practical paired-phase arrangement where interpair distance is great relative to intrapair distance. It shows that lower reactance if

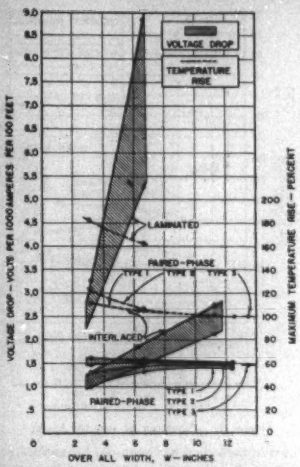


Figure 4. Effect of arrangement and spacing upon line-to-line impedance voltage drop and upon maximum temperature rise

Temperature rises are in per cent of that of the best arrangements. Paired-phase and laminated, $s = 3/4$ inch. Type 3 paired-phase, $d = 6$ inches. Bar size $1/4$ by 4 inches

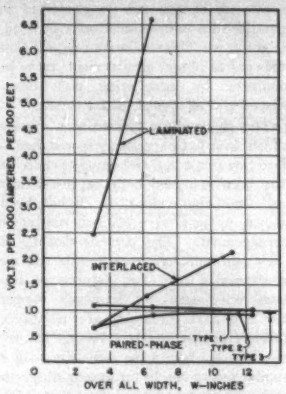


Figure 5. Effect of arrangement and spacing upon line-to-line reactance voltage drop

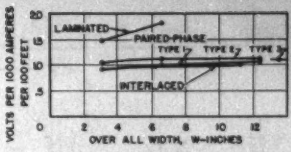


Figure 6. Effect of arrangement and spacing upon line-to-line resistance voltage drop

Copper temperature 75 degrees centigrade

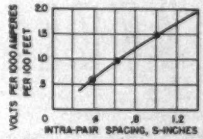


Figure 7. Effect of intrapair spacing, s, upon line-to-line reactance voltage drop of type-3 paired-phase arrangement

desired may be achieved by closer intrapair spacing.

Since the paired-phase arrangements with larger interpair spacings (type-1 or 2 arrangement with an over-all width of about six inches or more, or a type-3 arrangement) have superior characteristics from all considerations, there appears to be no practical reason other than space limitations for using smaller interpair spacings. Measurements made with these smaller spacings have been included, however, because of theoretical interest.

The inferior performance of the laminated arrangement needs no further comment, except that one may point out that there may be special instances, such as short connection straps where its use in preference to a more efficient arrangement may be justified by structural limitations.

In comparing the paired-phase and the interlaced arrangements, the practicability of obtaining various bus-bar spacings must be considered. Very close intrapair spacing is practical with paired-phasing, because bars may be offset into the vacant area surrounding each pair of bars at points where connections between adjacent bus-bar lengths or tap-off connections are to be made. Thus a clear space of one-fourth or three-eighths inch between paired-phase bars means a full spacing of that amount throughout the entire bus-bar run. The vacant area surrounding each pair also simplifies the problem of support and insulation. In the interlaced arrangement, because joint and tap-off connections must be made in the confined space between adjacent bars, clearances are necessarily decreased at these points, and insulation and installation problems are complicated. In interlaced arrangements a compromise must be made therefore between electrical properties, temperature rise, and structural complications; that compromise is not necessary with paired-phasing. These facts must be kept in mind when considering the data presented in this paper. For instance, an interlaced bus-bar system with an over-all width, w, of ten inches would have $1^3/_4$ inches between adjacent bars whereas a type-1 or type-2 paired-phase system of the same over-all width would have approximately $3^3/_4$ inches between pairs or a type-3 arrangement could be used without changing the electrical characteristics.

The relative current density for typical bus-bar arrangements is shown in Figure 8 in which the quantity plotted is the square of the magnitude of the current density. The measurements from the two faces of each bar have been averaged. This method of plotting gives an indication of relative energy losses, which are proportional to the areas under the curves. The more uniform current distribution within each bar and between bars of the paired-phase arrangements is evident. The small interpair effect is indicated by the slight difference in distribution between the two types of paired-phase arrangements. The nonuniform current distribution in both the laminated and the interlaced arrangements is caused by the greater reactance of the outside bars in these arrangements.

The analysis of energy losses in Figure 9 clarifies the performance of the paired-phase arrangement. The most important energy loss is the loss in that individual bar having the greatest energy loss, as this will determine the maximum "hot-spot" temperature rise, and in this respect paired phasing excels. Slightly lower average losses may be secured by using smaller interpair spacings, approaching the interlaced arrangement, but the greater resulting unbalance makes the individual bar losses higher rather than lower. Paired-phase housing losses, as shown in the lower portion of Figure 9, are negligible, and relative pair position has no influence upon these losses. Laminated-arrangement housing losses increase with wide spacing to such an extent that the average total loss increases even though individual bar loss decreases because of lessened proximity effect.

Equal and Opposite Currents Explain Paired-Phase Performance

Paired-phase performance may be understood by examining the distribution of current within the bus bars and the consequent magnetic-field effects in more detail. The magnitude and phase angle of the current density are shown in Figure 10, while the net currents in individual bars are shown in Figure 11. Only one paired-phase arrangement is shown, but

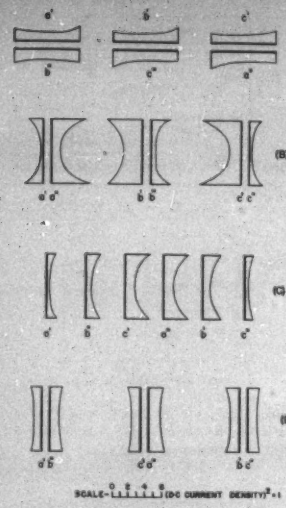


Figure 8. Current density squared in typical arrangements

A. Paired-phase type 3
d=6 inches s= 1/4 inch

B. Laminated
d=2 3/8 inches s= 3/8 inch
w=6 1/8 inches

C. Interlaced
d=2 1/4 inches w=11 1/4 inches

D. Paired-phase type 1
d= 5 1/4 inches s=3/8 inch
w=12 1/8 inches

the current distribution is similar in all paired-phase arrangements. There is a marked contrast in this respect between paired-phase and conventional arrangements. It is notable that the phase angle of the current density in the paired-phase arrangements is more uniform within each bar, and the net bar currents are more symmetrically disposed than in the other types of conductor arrangements.

The essence of paired-phase performance is that the currents in each close-spaced pair of bars are essentially equal and opposite. That is, each of the three phase currents (a, b, and c) divides into two component bar currents (a' and a'', b' and b'', c' and c'') which are nearly equal in magnitude and which differ in phase angle by nearly 60 degrees, so that the currents in each close-spaced pair of bars (such as a' and b'', or b' and c'', or c' and a'') differ in phase angle by nearly 180 degrees. The currents in each close-spaced pair are thus essentially similar to the currents in an isolated single-phase transmission system, even though each conductor of the pair is connected in parallel with another conductor in a different pair. This similarity suggests that the paired-phase arrangement may be analyzed by considering each close-spaced pair as a single-phase circuit.

The single-phase transmission system of two wide flat bars closely spaced face to face carrying equal and opposite currents has been analyzed both experimentally and mathematically.[8–12] It has been shown to be a very efficient conductor arrangement. The current density is very uniform, and consequently the a-c resistance is low. For instance, an isolated one-fourth- by four-inch copper bar will have an a-c to d-c resistance ratio of approximately 1.16, but the resistance of a bar of the same size with a similar return conductor five-eighths-inch away, center to center, is less than 1.02. The reactance of such a close-spaced pair is also very small. This means not only low-reactance voltage drop but small external magnetic field. In other words, the magnetic fields of the two equal and opposite currents cancel or neutralize each other. This explains the small interpair proximity effect and the negligible effect of magnetic or metallic surroundings upon either reactance or energy losses in the paired-phase arrangement.

The single-phase pair of closely spaced flat bars has many advantages over other low-loss single-phase arrangements such as concentric tubes. These advantages include the full exposure of both bars for heat dissipation, joining, support, insulation, and tap-offs. This single-phase arrangement has not been used generally in the past, but the recent advent of suitable commercial designs has led to the adoption of this arrangement for the service of large single-phase loads, with very satisfactory results.[13,14]

It is certainly unexpected and seems almost paradoxical that a most efficient method of transmitting large low-voltage polyphase currents should be one wherein the power is, in effect, transmitted single phase; but a comparison of paired phasing with conventional methods, considering all electrical, thermal, and structural factors, indicates that this is indeed true.

The beneficial results of the approximately equal and opposite currents in each close-spaced pair are further emphasized by the consideration of a condition where such a current division does not exist. The average ratio of a-c to d-c loss of the three-phase paired-phase arrangements (with larger interpair spacings) approximates 1.30 (see Figure 9), even though the current density within

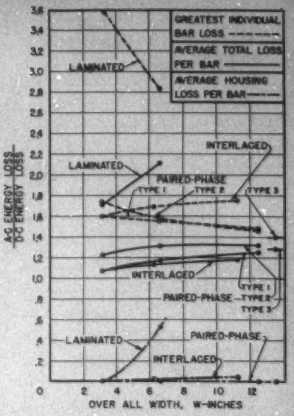


Figure 9. Analysis of energy losses

Loss in individual bar measured by exploring wires. Average total loss measured by wattmeter. Housing loss is difference between average total loss and average bar loss measured by exploring wires (not shown)

each bar is very uniform, because each bar carries nearly $1/\sqrt{3}$ rather than one half of the phase current. Losses are proportional to the square of the current: $(1/\sqrt{3})^2/(1/2)^2=1.33$. Conventional theory would suggest, therefore, that better performance would be obtained if the current in each bar could be made one half of the phase current, or, in other words, if the phase angle between the two currents in each close-spaced pair could be made 120 degrees instead of nearly 180 degrees, and the phase angle between the two currents of each phase, zero degrees instead of nearly 60 degrees. Such a condition may be produced by making a transposition at the mid-point of a bus-bar run, as shown in Figure 12, wherein each bar is paired with a different phase in each half of the run; for example, the a' bar is paired with a b-phase bar (b'') in the first half of the run and with a c-phase bar (c'') in the second half. The resultant performance is not, however, as might be expected:

Temperature rise	increased 31 per cent
Voltage drop	badly unbalanced and increased 217 per cent
Average energy loss	increased 54 per cent
Housing energy loss	becomes appreciable

In short, such a condition is undesirable, and all the desirable properties of the paired-phase arrangement are lost. This can be explained by the fact that there are no longer equal and opposite currents to cause a cancellation of magnetic effects in each close-spaced pair, and consequently interpair influence become

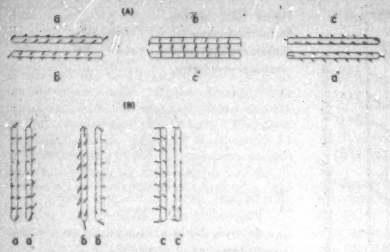


Figure 10. Details of current density

A. Paired-phase type 3 (same dimensions as Figure 8A)

B. Laminated (same dimensions as Figure 8B) Each vector shows magnitude and phase angle of current density at origin of vector

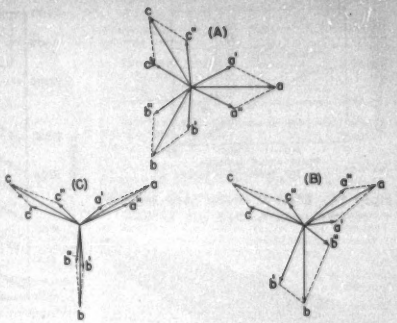


Figure 11 (right). Bar currents and phase currents

A. Paired-phase type 3 (same dimensions as Figures 8A and 10A)

B. Laminated (same dimensions as Figures 8B and 10B)

C. Interlaced (same dimensions as Figure 8C)

$a', a'', b', b'', c', c''$ indicate bar currents

a, b, c indicate phase currents

appreciable. This large interpair proximity effect is shown by the distorted current-density measurements in Figure 13.

Varying the phase angle between the currents in an isolated pair of nonenclosed bars further corroborates the effect of transposition. Test results shown in Figure 14 indicate that even under this simplified condition losses are least when the currents differ in phase angle by 180 degrees. Losses when the currents differ in phase angle by 120 degrees (which represents the condition with transposition) are intermediate between the paired-phase condition and the zero-degree phase-angle condition, corresponding to the laminated arrangement.

Calculation of Paired-Phase Bus Bars

The electrical characteristics of the paired-phase arrangement, including voltage drop and current distribution, are readily figured by electrical theory. A mathematical analysis of a simplified paired-phase arrangement is given in the appendix. These calculations indicate that the division of current between conductors in the paired-phase arrangement is not dependent upon any particular conductor shape but largely upon the grouping of the phases into pairs. Of course the conductor shape influences the distribution of current within each conductor. The mathematical analysis confirms experimental results in determining that the currents in each close-spaced pair become more nearly similar to single-phase as the interpair distance is increased and in fact approach the single-phase condition as a limit as the distance becomes infinite. This suggests and tests confirm that entirely satisfactory paired-phase performance may be secured when a steel housing completely surrounds each pair of bars.

The usual method of voltage-drop calculation based upon the assumption of equal and inphase currents in all bars connected to each phase will not give correct results when applied to paired-phase arrangements. Voltage drop can be calculated accurately, however, by application of formula 12 or 15 in the appendix. It has been found that for practical dimensions and purposes voltage-drop characteristics may be figured on the assumption of exactly equal and opposite currents in each pair of bars. Both the equivalent single-phase method of formula 15 and the more exact formula 12 give the correct resistance as well as reactance components of voltage drop. Sample calculations are given in the appendix.

Temperature-rise performance is not so readily calculated. Although the current and, hence, losses in each bar can be determined within a few per cent, heat transfer is so complicated by insulation, by proximity of other conductors, and by the enclosure, that tests using three-phase current are necessary for accurate information. Sufficient empirical data of course make possible the prediction of change in performance produced by minor variation in design.

Commercial Design of Paired-Phase Bus Bars

One practical commercial design embodying the paired-phase principle is shown in Figure 15. The flatwise arrangement was chosen because of the advantageous structural features, among which is the simple overlapping type of joining bus bars, insulation, and housing. This arrangement provides complete access to all bus-bar surfaces for cleaning and inspection before joining and complete accessibility of all bolts for maintenance By mounting the bus bars upon flat compression-type porcelain insulators, which in turn are supported on the housing, maximum mechanical and short-circuit strength are obtained. Also the dielectric strength between closely adjacent bus bars is readily improved by the use of a single flat sheet of insulation to supplement the one-fourth-inch minimum air space.

Tests indicate that this insulation sheet increases the temperature rise by less than two per cent. Other measure-

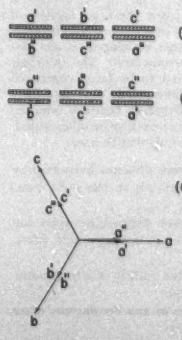


Figure 12 (left). Transposition to change current division

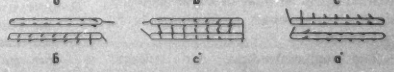
A. Arrangement in one half of bus-bar run

B. Arrangement in other half of bus-bar run. Each bar in A and B insulated except at beginning and end of run, where two bars of each phase are connected together

C. Resulting current division (compare with Figure 11A)

Figure 13. Nonuniform current density produced by transposition

(Compare with Figure 10A)



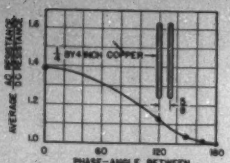


Figure 14. Effect of varying phase angle of currents in an isolated pair of bars

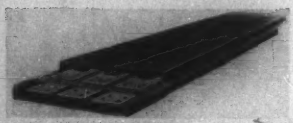


Figure 15. "Lo-X" bus duct utilizing paired-phase principle

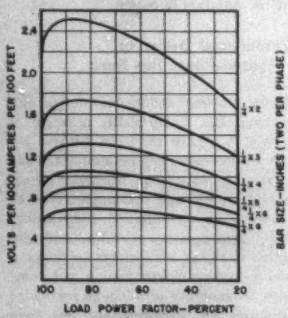


Figure 16. Line-to-line voltage drop of commercial paired-phase bus duct

Unbalance of voltage drop is less than width of curves. Resistance taken at copper temperature of 75 degrees centigrade $s = 1/2$ inch, d = bar width plus 2 inches

ments indicate that with all sizes of bus bars, the hot-spot temperature rise when the entire assembly is mounted edgewise is the same as when it is mounted flatwise; therefore, space limitations will determine the best position for any particular application. The shallow flat shape of the housing proves convenient in installation where close clearances are encountered.

Basic paired-phase principles as just outlined have been utilized in the design of numerous special fittings, such as elbows and tees, transformer taps, load tap-offs, and switchboard connections. Experience has shown that careful attention must be paid to these details if satisfactory over-all performance is to be obtained.

The temperature-rise and voltage-drop characteristics of a complete line of enclosed bus-bar system utilizing the paired-phase principle are given in Figures 16 and 17. Values are all based on actual tests of complete assemblies, including insulation and housing. These curves indicate the excellent performance that can be obtained with the paired-phase arrangement.

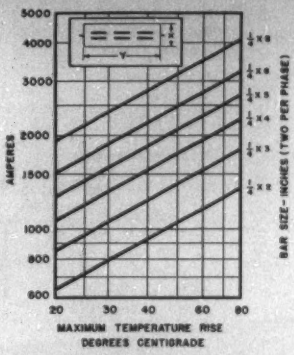


Figure 17. Temperature rise of commercial paired-phase enclosed bus duct indoors in still air

Totally closed steel housing

Bar Size	X	Y
1/4 by 2	4 1/2	by 14
1/4 by 3	4 1/2	by 17
1/4 by 4	4 1/2	by 20
1/4 by 5	4 1/2	by 23
1/4 by 6	4 1/2	by 26
1/4 by 8	4 1/2	by 32

Appendix. Mathematical Analysis of Current-Distribution and Voltage Drop in Paired-Phase Bus Bars

Consider Figure 18. The conductors are of arbitrary shape. The current density is assumed uniform over the cross section of each conductor. The length of the circuit is assumed to be large compared to the distances between conductors. The interpair distance is assumed to be large compared to the intrapair distance, so that as an approximation all distances between conductors not in the same pair may be taken equal. The following symbols will be used:

D_d = geometric mean distance between any two conductors not in the same pair, centimeters

D_s = geometric mean distance between any two conductors in the same pair, centimeters

D_r = geometric mean radius of any conductor, centimeters

r = d-c resistance of any conductor, ohms per centimeter

Figure 18. Simplified paired-phase arrangement with geometrical symmetry

E = voltage drop, volts per centimeter, line-to-neutral. (Note that voltage drops in body of this paper are all line to line)

I = current

a', b', c', a'', b'', c'' subscripts refer to conductor quantities. a, b, c subscripts refer to phase quantities.

$\omega = 2\pi$ times frequency in cycles per second

All logarithms are to base ϵ.

Since

$$I_a' + I_a'' + I_b' + I_b'' + I_c' + I_c'' = 0 \qquad (1)$$

the voltage drop in phase a may be written: (see reference 19, page 39, equation 55)

$$E_a' = E_a = I_a' r + 2\times 10^{-9} j\omega [I_a' \log (1/D_r) + I_b'' \log (1/D_s) + (I_a'' + I_b' + I_c' + I_c'') \times \log (1/D_d)] \qquad (2)$$

$$E_a'' = E_a = I_a'' r + 2\times 10^{-9} j\omega [I_a'' \log (1/D_r) + I_c' \log (1/D_s) + (I_a' + I_b'' + I_b' + I_c'') \times \log (1/D_d)] \qquad (3)$$

From symmetry

$$E_b = (-1/2 - j\sqrt{3}/2) E_a \qquad (4)$$

$$E_c = (-1/2 + j\sqrt{3}/2) E_a \qquad (5)$$

$$I_b' = (-1/2 - j\sqrt{3}/2) I_a' \qquad (6)$$

$$I_c' = (-1/2 + j\sqrt{3}/2) I_a' \qquad (7)$$

$$I_b'' = (-1/2 - j\sqrt{3}/2) I_a'' \qquad (8)$$

$$I_c'' = (-1/2 + j\sqrt{3}/2) I_a'' \qquad (9)$$

The solution of the above equations gives

$$I_a' = \left[\frac{1}{2} - \frac{\sqrt{3}}{2} \times \frac{10^{-9}\omega \log (D_d/D_s)}{r + 10^{-9} j\omega \log (D_d^3/D_r^3 D_s)}\right] I_a \qquad (10)$$

$$I_a'' = \left[\frac{1}{2} + \frac{\sqrt{3}}{2} \times \frac{10^{-9}\omega \log (D_d/D_s)}{r + 10^{-9} j\omega \log (D_d^3/D_r^3 D_s)}\right] I_a \qquad (11)$$

$$E_a/I_a = \frac{r}{2} + 10^{-9}\omega \left[\frac{1}{2} j \log \frac{D_d D_s}{D_r^2} + \left(\sqrt{3} \log \frac{D_d}{D_s}\right)\left(\frac{\sqrt{3}}{2} \times \frac{10^{-9}\omega \log (D_d/D_s)}{r + 10^{-9} j\omega \log (D_d^3/D_r^3 D_s)}\right)\right]$$

ohms per centimeter (12)

An interesting result is obtained by allowing D_d to become indefinitely large:

$$\mathrm{Lim}_{D_d \to \infty} I_a' = (1/\sqrt{3})(\epsilon^{j30^\circ}) I_a \qquad (13)$$

$$\mathrm{Lim}_{D_d \to \infty} I_a'' = (1/\sqrt{3})(\epsilon^{-j30^\circ}) I_a \qquad (14)$$

$$\text{Lim}_{D_d \to \infty} E_a/I_a = (4/3)(1/2)[r + 2\times 10^{-3} j\omega \log (D_s/D_r)]$$
ohms per centimeter (15)

Equations 13, 14, 15, and similar equations for the other phases represent a condition of equal and opposite or single-phase current in each close-spaced pair of bars. The term $[r + 2\times 10^{-3} j\omega \log (D_s/D_r)]$ in equation 15 is the impedance of one bar of a close-spaced-pair when carrying single-phase current.

Numerical substitution of practical values in equations 10, 11, and 12 shows that large variations in D_d have little effect upon I_a', I_a'', and E_a/I_a. Therefore, it seems reasonable that these equations may be used even when geometrical symmetry, as assumed in deriving these equations, does not exist.

Numerical Example

Consider a type-3 paired-phase arrangement:

Bar size $^1/_4$ by 4 inches
$r = 9.90\times 10^{-6}$ ohms per foot $= 324\times 10^{-6}$ ohms per centimeter
$s = ^5/_8$ inch
$d = 6$ inches

From the formula and curves of reference 17

$D_r = 0.2235\ (4 + 0.25) = 0.950$ inch $= 2.41$ centimeters
$D_s = 1.372$ inches $= 3.49$ centimeters

GMD of two bars in adjacent pairs (6 inches center to center) = 5.75 inches
GMD of two bars in outside pairs (12 inches center to center) = 11.88 inches

No readily usable values for *GMD* of the diagonally located bars are available; therefore, consider diagonal *GMDs* the same as above. As a working approximation the average may be taken as

$$D_d = \sqrt[12]{(5.75)^8 (11.88)^4} = 7.33 \text{ inches} = 18.62 \text{ centimeters}$$

From equation 10

$$I_a' = 0.525\epsilon^{j29.5^\circ} I_a$$

From equation 11

$$I_a'' = 0.591\epsilon^{-j24.4^\circ} I_a$$

From equation 12

$E_a/I_a = (6.17 + j5.71)10^{-6}$ ohms per foot (line to neutral)

From equation 15

$E_a/I_a = (6.58 + j5.65)10^{-6}$ ohms per foot (line to neutral)

By measurement (average of three phases)

$$I_a' = 0.544\epsilon^{j31.3^\circ} I_a$$
$$I_a'' = 0.574\epsilon^{-j33.6^\circ} I_a$$

$E_a/I_a = (6.35 + j5.61)10^{-6}$ ohms per foot (line to neutral)

The differences between measured and calculated values are in the directions that would be expected in view of the various assumptions made. The phenomena of Figure 14, neglected in the calculations, makes the phase angle between I_a' and I_a'' more nearly 60 degrees than calculated from equations 10 and 11. The resistance calculated from equation 12 is lower than measured, because slight nonuniform current density in individual bars is neglected. That calculated from equation 15 is higher, because the magnitude of the bar currents is less than the $0.577\ I_a$ assumed by this method. A small correction could be made for nonuniform current density by applying published formulas for skin effect in a single-phase pair of flat bars.[11] Reactances agree within experimental error.

Calculation of impedance by the conventional assumption that $I_a' = I_a''$, vectorially (see reference 17, equations 15 to 20) gives

$E_a/I_a = (4.95 + j8.27)10^{-6}$ ohms per foot (line to neutral)
$E_b/I_b = E_c/I_c = (4.95 + j16.55)10^{-6}$ ohms per foot (line to neutral)
Average $= (4.95 + j13.80)10^{-6}$ ohms per foot (line to neutral)
Measured with $I_a' = I_a''$ (produced by use of a transposition, Figure 12):
Average $= (9.87 + j19.02)10^{-6}$ ohms per foot (line to neutral)

The conventional method of calculation, therefore, does not give correct results for ordinary paired-phase arrangements, because current distribution is not as assumed. On the other hand, when bar currents are as assumed, the current density within each bar is not uniform, and, in addition, the steel housing causes extra losses and higher reactance.

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An Electromechanical Calculator for Directional-Antenna Patterns

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Synopsis: An electromechanical calculator has been designed for the rapid solution of directional-antenna patterns. After the desired antenna parameters have been set up, the machine automatically draws the field-intensity curve to any desired scale on a sheet of polar co-ordinate paper and indicates the rms value for drawing a circle of the equivalent nondirectional pattern.

The fundamental design of the calculator does not limit the number of antennas that can be used in the directional array. As the number of antennas is increased, the greater the degree of control is possible to mould the radiation pattern into the desired shape.

Not only is the horizontal directional field-intensity pattern, such as used in broadcast practice, readily available, but the field-intensity contours at any elevation angle can be drawn with equal ease. The vertical radiation characteristics of the several antennas can be selected at will. This makes it possible to explore the solid contour surface of the whole hemisphere in a relatively short time and also determine the total power radiated from the directional-antenna system. The machine is also suitable for calculating the solid contour surface of the radiation pattern from a parallel horizontal antenna array.

TO anyone who has had the task of designing a directional-antenna array, the need of some short cut to reduce the tedium of laborious calculations has been very apparent. To meet this need a number of schemes has been brought forth, ranging from early graphical methods to actual measurements on models, from purely mechanical to purely electrical devices. These devices have varying degrees of usefulness, and all meet to a large degree the requirements of lessening the time required to explore the number of varying parameters necessary to meet some special case.

Extended tables systematizing patterns of two tower arrays have been published.[1-4] These diagrams are very helpful to show trends, even though the designer may in the final analysis have to calculate very precisely the pattern after deciding upon a suitable range of spacings and phasings. The authors felt that a systematization of three tower arrays would be of very real value to the industry. Therefore, in taking up the problem of developing an antenna-pattern calculator, they had in mind not only its immediate use as at first outlined, but also the ultimate accurate and quick development of a great number of patterns. After considering carefully the merits of various methods, it was decided that an electromechanical device could be made to combine the accuracy and simplicity of the mechanical method with the speed and flexibility of the electrical method.

The usual problem in broadcast practice is to mould the radiation pattern into the desired shape to cover the service areas and give the required protection to other radio stations. As a matter of economics, it is desirable to do the job with the minimum number of antennas. With severe requirements, the number of antennas must be increased until the radiation pattern can be moulded into the desired shape. This electromechanical calculator was designed primarily to handle this type of problem. It is not necessary to assume images on the basis of a perfect earth. The only requirement is that the vertical radiation characteristic of the several antennas be known when it is desired to determine the solid contour surface over the whole hemisphere.

It is also possible to solve for the solid contour surface of horizontal radiators located above the surface of the earth. In this case, the horizontal radiation characteristic of the individual antennas in free space must be known. The images in this case must be set up on the machine just as the actual antennas are set up. If the horizontal antennas are perpendicular to and bisected by a vertical plane, then the contours are run at constant angles to this perpendicular plane, just as the various elevation contours are run in the case of vertical antennas. In other words, the contours are run as if the antennas were vertical, and then the contour surface is rotated 90 degrees to locate properly the antennas above the surface of the earth. Only that part of the contour surface is useful that appears above the surface of the earth. For such an array the contour surface will be symmetrical to the vertical plane passing through the center of the antennas.

A more general case is to have horizontal parallel antennas without requiring their centers to bisect a vertical plane. In this case those horizontal antennas and their images, that are not bisected by a vertical plane, must have their phase adjusted by for each contour to correct for the space phase difference. These adjustments of phase are made on the assumption that the observation point is located at infinity, which is the same assumption that is ordinarily used for the antenna spacing. For this more general case the pattern will be unsymmetrical about any vertical plane, and the contour surface will have to be run for both ends of the array.

Design Consideration

In consideration of the problem of systematizing directional-antenna patterns, it is desirable to have considerable flexibility, accuracy, and speed in the machine. Since the time involved to do this job by hand is prohibitive, one can afford to spend considerable time and effort in perfecting a machine to the point that it will give, with sufficient accuracy, this valuable engineering information. The design and development of such a machine, incidentally, involves the solution of a number of rather interesting problems.

The purely mechanical calculator[5,6] has simplicity and accuracy depending upon the preciseness with which the individual mechanical parts are made. However, in its usual forms, it lacks considerable flexibility and speed for calculating all the desired factors involved in a directional pattern. The usual design of these calculators will give the horizontal pattern for three antennas, and, if the antennas are identical, the vertical patterns can be determined without much difficulty. Its operation depends upon one vector being fixed and used as the reference with the vectors of the other two antennas revolving about its ends in the proper fashion. The handling of more than three antennas becomes mechanically involved, because the additional vectors must revolve about the ends of the free-ended vectors. Recording the patterns accurately and automatically with such a device is exceedingly difficult, because the distance between the free-ended vectors must be

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The authors express appreciation to all the operating engineers on the WHK-WCLE staff who have contributed in making the electromechanical calculator a success.

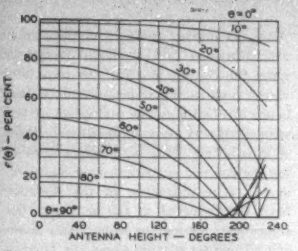

Figure 1. Vertical radiation characteristic as a function of electrical height

measured and recorded accurately at all points. If readings are taken at periodic intervals, these values must again be used in a separate operation to determine the rms value of the pattern. This is a very important quantity if the pattern is to be used for a definite power into the system. Even then there is the question of the power used in the high angle radiation. It usually takes longer to determine the rms value than it does to determine the pattern itself. A more satisfactory method is to use an equation involving Bessel functions to determine the rms value.[1] Appendix I gives the general form of this equation with an illustrative example.

The purely electrical form of calculator may place the directional-antenna pattern on an oscilloscope screen. This scheme is rapid, being visual, can be altered instantaneously by changing the various antenna parameters at will, and is not limited to the number of antennas in the system. The rms value can be read from a meter directly. The limitation of this scheme is primarily lack of accuracy, depending of course upon the electrical design.

The authors have put into operation at the transmitting plant of WHK–WCLE an electromechanical directional-antenna pattern calculator which will automatically draw the horizontal pattern of a four-element array with the possibility of adding as many more elements as desired. This machine will also automatically draw the field-intensity contours at various elevation angles. These data readily yield the vertical pattern in any direction from the antenna system. In addition to this, the machine measures the rms value of the pattern as it is drawn. Hence, the volume of the solid radiation pattern is readily determined by a simple computation. From this information the actual power radiated from the antenna system can easily be computed.

The electromechanical calculator accomplishes its purpose by starting with a simple mechanical system, converting to an electrical system for flexibility, and finally converting back to a mechanical system to draw the curve. The mechanical portion of the calculator consists of a turntable to hold the polar co-ordinate chart paper. This turntable is driven by a variable-speed motor which in turn drives the several mechanical cosine generators. These generators in effect rotate the second, third, and fourth antennas around the first or reference antenna. The mechanical cosine generators are rack-geared to phase-shifting transformers. At this point the mechanical vector is converted into an equivalent electrical vector. All of the electrical vectors can then be added in series and the resultant represents the field intensity in the given direction in space as indicated by the orientation of the turntable carrying the polar co-ordinate chart paper and the elevation angle. An automatic voltagraph converts this electrical magnitude into an equivalent mechanical magnitude to drive the radial inking pen and planimeter. The inking pen draws the pattern while the planimeter measures the rms of the pattern. Usually, after the directional pattern is finished, the rms circle is drawn on the polar co-ordinate chart as additional valuable information.

Generalized Equation

The electromechanical calculator in reality is an equation solver. In this case the equation is of a particular variety, and the machine must be adapted to handle the various parameters in the equation. The method of operation of the machine can best be explained after considering the general nature of the equation to be solved.

For a directional antenna array of n antennas, the generalized equation is

$$\boldsymbol{E} = \sum_{k=1}^{k=n} E_k f_k(\theta) \epsilon^{j\beta_k} \qquad (1)$$

where

$\boldsymbol{E}$ = the total effective field-intensity vector for the antenna array with respect to the voltage reference axis

k = the kth antenna in the system

n = the total number of antennas in the complete directional-antenna array

E_k = the horizontal magnitude of the field intensity produced by the kth antenna

$f_k(\theta)$ = vertical radiation characteristic of the kth antenna (unity along the horizon)

θ = elevation angle of the observation point P measured up from the horizon in degrees

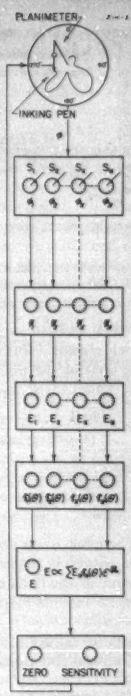

Figure 2. Symbolic representation of the electromechanical antenna-pattern calculator

A—Motor - driven turntable carrying polar co-ordinate chart paper. The orientation of the observer is represented by ϕ

B—Mechanically driven cosine wave generators with adjustments for antenna orientations ϕ_k, spacing S_k and elevation angle θ

$S_k \cos(\phi_k - \phi) \cos\theta$

C—Mechanically driven phase-shifting transformers with adjustments for antenna current phase Ψ_k

$\beta_k = S_k \cos(\phi_k - \phi) \cos\theta \Psi_k$

D—Electrical magnitude adjustment of horizontal field intensity E_k, $E_k \epsilon^{j\beta_k}$

E—Electrical magnitude to give vertical radiation characteristic $f_k(\theta)$ $E_k f_k(\theta) \epsilon^{j\beta_k}$

F—Summation of electrical vectors and total electrical magnitude control of field intensity E

G—Voltagraph converts electric field intensity E to an equivalent mechanical magnitude. It is provided with zero and sensitivity adjustments

The output of the voltagraph drives the inking pen to draw the resulting pattern on the polar co-ordinate chart paper. Also, a planimeter is driven to measure the area of the pattern

$\epsilon^{j\beta_k}$ = unity vector determining the direction of the voltage vector of the kth antenna

$\epsilon = 2.718\ldots$ the base of natural logarithms

$j = \sqrt{-1}$ imaginary j operator

$$\beta_k = S_k \cos(\phi_k - \phi) \cos\theta + \Psi_k \qquad (2)$$

= phase relation of the voltage (or current) in the kth antenna with respect to the voltage reference axis

S_k = electrical length of the spacing of the kth antenna from the space reference point

ϕ_k = true horizontal azimuth, orientation of the kth antenna, with respect to the space reference axis

ϕ = true horizontal azimuth angle of the direction to the observation point P (measured clockwise from true north)

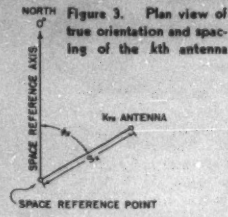

Figure 3. Plan view of true orientation and spacing of the kth antenna

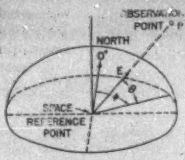

Figure 4. Vector representation of the total field intensity in space

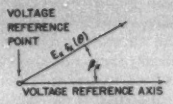

Figure 5. Vector representation of the field intensity of the kth antenna

Ψ_k = electrical phase angle of the voltage (or current) in the kth antenna with respect to the voltage reference axis

For a vertical antenna having a sinusoidal current distribution with a current node at the top, the vertical radiation characteristic takes on the form

$$f_k(\theta) = \frac{\cos(h \sin\theta) - \cos h}{(1 - \cos h)\cos\theta} \qquad (3)$$

where

h = electrical height of the antenna in degrees.

The other terms are as defined above. The curves in Figure 1 represent the solution of equation 3 over the most useful range of antenna heights.

Machine Solution of Generalized Equation

The electromechanical antenna-pattern calculator solves the generalized equation as shown symbolically in Figure 2. The position of the observer, the placement of the antennas, and the phase of antenna currents determine the direction of the various antenna vector voltages. These adjustments are all mechanical. The magnitude of these vectors are controlled electrically and are added for the total effective field intensity. This field intensity is then converted into an equivalent mechanical magnitude to drive the inking pen and planimeter.

The direction of the inking pen from the zero-degree reference orientation of the turntable represents the orientation ϕ of the observer from the antenna system. The turntable which is driven by a variable-speed motor is geared through clutches to all the cosine wave generators. The orientation of the kth antenna, for example, from true north is accomplished on the calculator by locking the turntable so that the inking pen is true north. The kth antenna cosine-wave-generator clutch is then released and turned to give the desired orientation ϕ_k in degrees as indicated on the orientation dial. The clutch is then locked into position. The spacing S_k of the kth antenna measured from the space reference point is an amplitude adjustment, measured in electrical degrees on the spacing arm, of the cosine wave generator. These two adjustments locate the kth antenna as illustrated in Figure 3. The adjustments thus far give the function $S_k \cos(\phi_k - \phi)$ for the horizontal pattern.

The cosine wave generator drives a phase-shifting transformer through a rack and gear. This mechanism is so proportioned that if the observer moves around the antenna, by rotating the turntable, the phase of the current in the kth antenna will shift the same number of electrical degrees that the number of electrical degrees from the observer to the antenna changes. The phase of this current is zero in the kth antenna when the voltage vector lies along the voltage reference axis. For this condition the distance from the observer to the space reference point is equal to the distance from the observer to the kth antenna. The phase Ψ_k is adjusted by a clutch arrangement on the shaft of the phase-shifting transformer. Any electrical phasing measured in degrees can be set mechanically on the phase dial associated with this clutch. With this adjustment added, the function becomes $S_k \cos(\phi_k - \phi) + \Psi_k$ for the horizontal pattern.

All of the mechanically adjusted parameters are represented in equation 2.

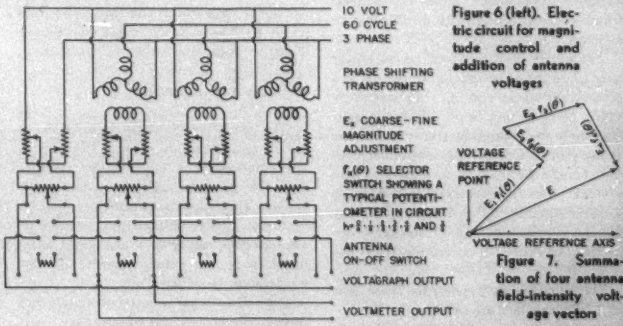

Figure 6 (left). Electric circuit for magnitude control and addition of antenna voltages

Figure 7. Summation of four antenna field-intensity voltage vectors

Along the horizon $\cos\theta = 1$, and the function described in the above paragraph gives the correct answer. At some elevation angle $\cos\theta$ becomes less than unity; hence this factor can be multiplied by the spacing S_k and an equivalent new closer spacing set up. This is the effect of viewing the antenna system at some elevation angle. The difference in the distance from the observer to the antennas becomes less; hence, the same result is accomplished by staying along the horizon and placing the antennas closer together. Directly over the antenna system all antennas are the same distance; hence, the product $S_k \cos\theta$ must go to zero. The function for any direction is $S_k \cos(\phi_k - \phi)\cos\theta + \Psi_k$.

The direction of the observation point P in terms of the true orientation ϕ and elevation angle θ is illustrated in Figure 4. The magnitude of the total effective field intensity E is represented along the direction of the line from the space reference point toward the observation point P for convenience in drawing the polar charts. The field intensities at a given elevation angle can be duplicated with an equivalent horizontal pattern, using closer antenna spacing and modified field intensities.

The field intensity of the kth antenna as given in equation 1 is vectorially represented in Figure 5. The phase angle β_k is controlled by the mechanical adjustments which in turn controls the phase of the output voltage of the phase-shifting transformer. The magnitude of the output voltage E_k is controlled by a potentiometer. See Figure 6. For field-intensity magnitudes at elevation angles, this value must be controlled in accordance with the vertical radiation characteristic $f_k(\theta)$ of the antenna. For convenience in running contours at the various elevation angles, vertical-radiation-

characteristic potentiometers are used for antennas having heights in multiples of an eight-wave length plus one position which is adjustable to any other desired vertical pattern. These vertical-pattern potentiometers speed up the work and lessen the chance of making errors. The electric circuit involving these parameters is illustrated in Figure 6.

The total effective field-intensity vector $\boldsymbol{E}$ is the summation of all the vector voltages from the various antennas. In this calculator these voltages are added in series. The resulting summation of the vector voltages for a four-element directional-antenna system is illustrated in Figure 7. Only the angles of these vectors vary as the orientation from the antenna system changes. Both the angle and magnitude changes as the elevation angle θ is varied.

The magnitude E of the total effective field-intensity vector $\boldsymbol{E}$ is now converted into an equivalent mechanical magnitude in order that the radial drawing pen can be driven in such a way as to produce the field-intensity pattern on the polar co-ordinate chart paper. A rapid self-balancing precision potentiometer circuit was developed to accomplish this result. Adjustments are provided to make zero voltage correspond to the center of the polar co-ordinate chart paper. A sensitivity adjustment makes it possible to select any reasonable scale for a given output voltage magnitude E. Usually in systematizing patterns, the magnitude of the maximum lobe of the pattern is adjusted to fall on a given circle. This usually requires an adjustment of the sensitivity for each pattern.

Enough power is supplied from the balancing mechanism to drive, in addition to the pen, a planimeter which rolls and slides on the chart paper and measures the area of the chart. By means of a table the operator can immediately determine the rms value of the pattern and draw this circle on the chart with the drawing pen controlled by a single antenna which is nondirectional.

Speed

The machine is driven by a variable-speed motor. For simple patterns the speed can be increased somewhat and the machine still maintain the required accuracy. For ordinary systematization work it takes from three to five minutes to complete a pattern. This involves setting the parameters and drawing the pattern and the rms circle. The solid contour surface can be investigated and recorded on the chart paper in less than an hour. This usually involves a total of nine contours placed three to a chart.

Accuracy

The machine is operated from a 220-volt three-phase 60-cycle source at the present time. Line-voltage fluctuations are the greatest source of error. The machine depends upon these voltages remaining constant while the pattern is being run. Originally it was planned to provide an independent source of power free from fluctuations, but this had to be abandoned for the duration of the war.

A number of different makes of phase-shifting transformers was tested, and the best, which are being used in the present machine, showed a maximum error of three per cent. This appeared to be satisfactory for the systematization work. If desired on special jobs, checks can always be made, with a vacuum-tube voltmeter, of all the voltages in the system, to increase the magnitude accuracy to that of the voltmeter. The error in phase angle checks within one degree.

In the systematization work, the antenna orientations ϕ_2 are advanced approximately one degree to compensate for the lag in the drawing pen. This lag is a function of the speed of the turntable; hence, by slowing the turntable down it can be practically eliminated.

The precision potentiometer can be adjusted so that the mechanical magnitude tracks with the electrical magnitude and the balance point is always within one per cent of the full-scale value.

The polar planimeter used to measure the area of the charts varies somewhat in its readings but usually can be relied upon to within one per cent.

Chart Paper

Two varieties of special chart paper have been prepared. One is a simple ten-inch circle with crosslines printed on a 12-by-12-inch sheet and is used primarily for the systematization work. Three such charts with patterns were tacked to cover lid of the calculator illustrated in Figure 10. The patterns are all for three tower antennas. The numbers at the bottom completely specify parameters.

The finely engraved chart paper was also prepared on 12-by-12-inch sheets but can be trimmed down to 11 by 12 inches to fold into a standard notebook of $8\frac{1}{2}$ by 11 inches. The engravings on this chart consist of a complete circle ten inches in diameter, divided with radials to single degrees and numbered every ten degrees clockwise from the top. The ordinates are divided into ten parts to the inch with heavy markings every half inch. Figure 8 illustrates this chart paper with the horizontal and eight elevation angle contours crowded on one sheet. The legend "Directional-Antenna Parameters" in the upper right-hand corner specifies all the conditions imposed upon the system. The legend in the lower right-hand corner specified the firm name, date, manufacturer and pattern number. This chart paper is now available to the public[8] with or without the blocks in the corners in a light or heavy weight of paper. The chart paper is printed with a brown ink for ease in making photostats or blueprints.

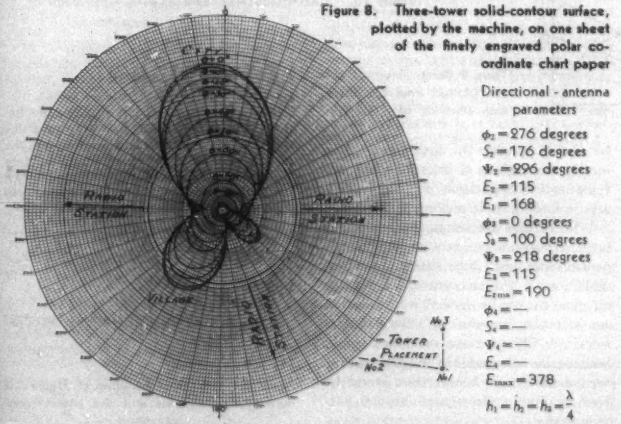

Figure 8. Three-tower solid-contour surface, plotted by the machine, on one sheet of the finely engraved polar co-ordinate chart paper

Directional - antenna parameters

$\phi_2 = 276$ degrees
$S_2 = 176$ degrees
$\Psi_2 = 296$ degrees
$E_2 = 115$
$E_1 = 168$
$\phi_3 = 0$ degrees
$S_3 = 100$ degrees
$\Psi_3 = 218$ degrees
$E_3 = 115$
$E_{rms} = 190$
$\phi_4 = —$
$S_4 = —$
$\Psi_4 = —$
$E_4 = —$
$E_{max} = 378$
$h_1 = h_2 = h_3 = \frac{\lambda}{4}$

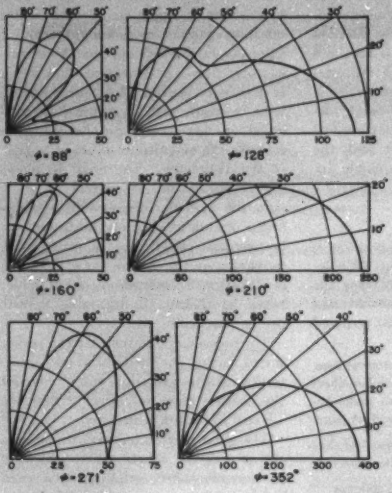

Figure 9 (left). Vertical patterns plotted from the elevation contours of Figure 8

Figure 10. Electromechanical antenna-pattern calculator

Vertical Patterns

Vertical-plane radiation patterns as shown in Figure 9 are readily obtained from the elevation contours in Figure 8. The vertical patterns are important when considering sky-wave interference problems between radio stations.

Illustrations

The complete machine is shown in Figure 10. The magnitude controls are on the left-hand panel, followed by the turntable and cosine wave generator panels. A supply of chart paper is held in a pocket under the table, convenient to the operator. The master-control power switch is on the left-hand front leg. The voltagraph-control amplifiers and power transformers are located on the shelf under the table. The whole unit is on wheels and is provided with a dust cover lid.

Figure 11 is a close-up view showing details of the turntable and one cosine wave generator.

Conclusions

After three months of continuous operation, the machine has proved to be a speedy means of securing directional-antenna patterns. The systematization work which is progressing steadily will be available at a later date.

The machine is extremely valuable when one is searching for a directional-antenna pattern to meet certain specific requirements. Many patterns can be drawn quickly to investigate thoroughly the regions of interest. The systematization of patterns will aid materially in finding these regions of interest.

With care of operation, the results are believed more accurate than can be expected from most directional-antenna installations. The acceptance of such a machine by the profession will remove a considerable amount of the routine work. A few of these machines would perhaps be adequate to supply all the needed patterns; hence, they could be used to offer a directional-antenna pattern service.

Appendix I

The general form of the equation for determining the root-mean-square value for the directional-antenna pattern involves the product of the field intensity of each antenna multiplied by the field intensity of every antenna in the system. In mathematical form this can be written

$$E_{rms} = \sqrt{\sum_{p=1}^{p=n} \sum_{q=1}^{q=n} E_p E_q \cos(\Psi_p - \Psi_q) J_0(S_{pq})} \quad (4)$$

where

E_{rms} = root-mean-square effective field intensity

Figure 11. A close-up view of Figure 10 showing the turntable and one cosine wave generator

p = the pth antenna in the system
q = the qth antenna in the system
n = the total number of antennas in the complete directional antenna array
E_p = horizontal magnitude of the field intensity produced by the pth antenna
E_q = horizontal magnitude of the field intensity produced by the qth antenna
Ψ_p = electrical phase angle of the voltage (or current) in the pth antenna with respect to the voltage reference axis
Ψ_q = electrical phase angle of the voltage (or current) in the qth antenna with respect to the voltage reference axis
$J_0(S_{pq})$ = Bessel function of the first kind and zero order of the spacing S_{pq}, in radians, between the pth and qth antennas

In this equation when $p = q$, the terms are simply the square of the antenna field intensity, because the cosine and Bessel function terms each reduce to unity. For example in a three-tower array the application of equation 4 results in

$$E_{rms} = \sqrt{\sum_{p=1}^{p=3}\sum_{q=1}^{q=3} E_p E_q \cos(\Psi_p - \Psi_q) J_0(S_{pq})}$$

$$= \sqrt{\begin{aligned} &E_1^2 + E_2^2 + E_3^2 \\ &+2E_1E_2\cos(\Psi_1-\Psi_2)J_0(S_{12}) \\ &+2E_1E_3\cos(\Psi_1-\Psi_3)J_0(S_{13}) \\ &+2E_2E_3\cos(\Psi_2-\Psi_3)J_0(S_{23}) \end{aligned}} \quad (5)$$

If the parameters for the three-tower directional-antenna array illustrated in Figure 8 are substituted in equation 5 the horizontal rms field intensity becomes

$$E_{rms} = \sqrt{\begin{aligned} &168^2+115^2+115^2 \\ &+2(168)(115)\cos(0-296)\times J_0(3.07) \\ &+2(168)(115)\cos(0-218)\times J_0(1.745) \\ &+2(115)(115)\cos(218-296)\times J_0(3.37) \end{aligned}}$$

$$= \sqrt{\begin{aligned} &168^2+115^2+115^2 \\ &+2(168)(115)(0.4384)(-0.2829) \\ &+2(168)(115)(-0.7880)(0.3719) \\ &+2(115)(115)(0.2079)(-0.3587) \end{aligned}}$$

$$= 191$$

This shows an error of approximately one half of one per cent in the value 190 measured by the planimeter on the machine.

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Mobile Capacitor Units for Emergency Loading of Transformers in Open Delta

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Synopsis: Loading of closed delta banks of substation transformers to a point approaching safe thermal limit results in severe overloading of two transformers as well as decided unbalance in voltage and current when operated in open delta as a result of the failure of one transformer. By the use of mobile capacitor units with capacitors arranged in two unequal groups, the load on two transformers in open delta is reduced, regulation improved, voltage and current are balanced within operating limits, and with the aid of fans, the top oil temperatures—and consequently, the copper temperatures—are kept within safe limits. This permits proper loading of transformers in closed delta, a relatively short interruption to service or reduction in load upon failure of one transformer in a bank, and a reduction in number of transformers required for emergency use.

TO maintain satisfactory service on a power system, mobile equipment such as railway-car-mounted substations[1] and highway trailer portable transformers have been found very effective. These portable transformers were designed to be used in case of the failure of more than one transformer in a bank. To maintain service in event of failure of a single transformer in a delta-delta bank, transformers of sufficient capacity were used to permit open delta operation without materially damaging the insulation from overheating during the repair of the damaged unit. This method should no longer be used, for it is now imperative that substation transformers be loaded to a point approaching the safe thermal limit. With transformers so fully loaded, the failure of one transformer in a bank will necessitate an interruption to service, or reduction in load for sufficient time to permit moving and installing additional transformer capacity, since operation in open delta would load the two transformers to 173 per cent of the closed delta loading. Operating at this overload would result in severe overheating of the two transformers and a very pronounced unbalance in voltage and current. Figure 1 shows calculated regulation of a typical bank of transformers in open delta with the two transformers operating at 173 per cent of rating. In addition to time and effort required to move and install emergency transformer capacity, this method requires a considerable stock of transformers of assorted sizes, voltages, and impedances on a system having a number of primary voltages. For example, the primary voltage of substation transformers on the system with which the authors are associated includes: 100 kv, 44 kv, 33 kv, 22 kv, 13.2 kv, 6.6 kv, and 2,400 volts.

An alternate method consists of open delta operation with the use of mobile capacitors and fans. As the power factor of load on substation transformers of the system on which these capacitors are used is ordinarily between 70 per cent and 80 per cent, the regulation of transformers operating at approximately 173 per cent of normal load in open delta is large and badly unbalanced. This excessive regulation and unbalance is corrected by connecting capacitors across the phase lagging the open delta and across the open delta. Figure 2A shows the calculated regulation of a bank of two 750-kva, 35-degree, 44,000–2,400-volt transformers both with and without capacitors and

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with a maximum load of 3,125 kva, the power factor being 74 per cent. Figure 2B shows transformer currents in each case. Capacitance of 1,080 kva was used across the phase lagging the open delta and 540 kva across the open delta. In making these calculations it was assumed for all loads that the load currents were equal in each phase and 120 degrees apart. The voltages on the source side of the transformers were assumed to be equal for each phase and 120 degrees apart. The power factor of 74 per cent was taken with respect to the balanced primary voltages. The per cent voltages shown on Figure 2A are the calculated values on the load side of the transformer bank. The curves of voltage are therefore somewhat distorted from what they would be in an actual application, because the primary and secondary voltages both would be somewhat unbalanced. In this application, however, when using capacitors, the voltage on both the primary and secondary windings of the transformer bank will be balanced at a load of 2,500 kva. This is shown for the load voltages on the curves of Figure 2A.

The loading of transformers in open delta with capacitance properly applied may be illustrated by the following example:

Assume a safe loading of three transformers to be 300 kva, the power factor, 75 per cent, and the kilowatts, 225. The load on each transformer, 100 kva, 75 kw.

In open delta, the loading of each transformer will be 173 kva, less a small decrease in output due to regulation.

If capacitance should be added to bring the power factor of each transformer to 100 per cent, the loading of each would be 112.5 kva, plus the capacitor losses, which are small.

Should capacitance be added to bring the power factor of the transformer which is connected across the phase lagging the open delta to 90 per cent, the load on each transformer will average approximately 125 kva, plus capacitor losses. This is still a satisfactory condition, as the regulation will be good, and transformers can be cooled with fans.

Method of Connecting Capacitance

Tests were made to determine the most effective application of capacitance to the phases of an open delta bank with loads of various power factors. A capacitance ratio of two parts across the phase lagging the open delta to one part across the open delta gave satisfactory results. This connection is shown schematically in Figures 4, 5, and 6, and is used in all mobile units. Thirty-six 15-kva capacitors rated 600 volts with 2,400-volt insulation to case were installed in each mobile unit. The groups of 12 and 24 capacitors were arranged for connection in parallel for 600-volt operation and four series-parallel for 2,400-volt operation. A mobile unit of this size was determined upon as a single unit is applicable to banks with loads as small as 300 kva and to banks with loads as large as approximately 1,500 kva, there being some 400 banks within these limits on the system on which these mobile capacitors are used. As can be seen in Figure 3, a unit of this capacity is comparatively small and can be handled easily.

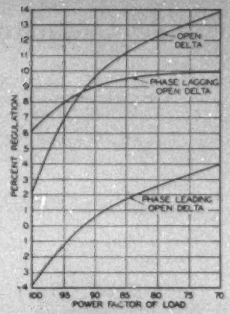


Figure 1. Calculated phase regulation of open-delta bank with transformers loaded to 173 per cent of rating

Transformer rating:
300 kva, 35 degrees centigrade rise
Voltage, 40,000/575

Regulation:
100 per cent power factor—0.94 per cent
90 per cent power factor—3.70 per cent
80 per cent power factor—4.65 per cent

Figure 3. Mobile capacitor unit attached to towing vehicle

Tests and Operating Results

Data were obtained from capacitors in use as well as in tests in which one transformer was disconnected to give open delta connection. Figure 4 shows test on bank of 300 kva, 35-degree rise, 44,000/575-volt transformers with a peak load of over 1,300 kva and with complete readings taken with loads between 1,100 and 1,200 kva. Temperature curves show transformer temperatures while operating in closed delta, self-cooled, and in open delta, fan-cooled, with capacitors. One set of readings was taken with 25 per cent of the capacitors disconnected, but with the same ratio of 2 to 1 applied to the phase lagging the open delta and across the open delta. This test, as well as data in Figures 5 and 6, illustrates the wide range permissible in amount of capacitance used. Figure 5 shows test of bank

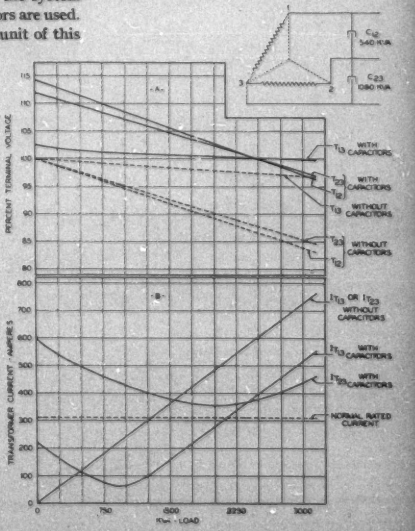


Figure 2. Calculated performance of transformers in open delta with and without capacitors

Transformer rating:
750 kva, 35 degrees centigrade rise
Voltage: 44,000—2,400

Regulation:
100 per cent power factor—0.94 per cent
90 per cent power factor—3.60 per cent
80 per cent power factor—4.75 per cent
74 per cent power factor—5.00 per cent

Power factor of load:
74 per cent

Per cent impedance:
0.9+j6.5 on 750 kva

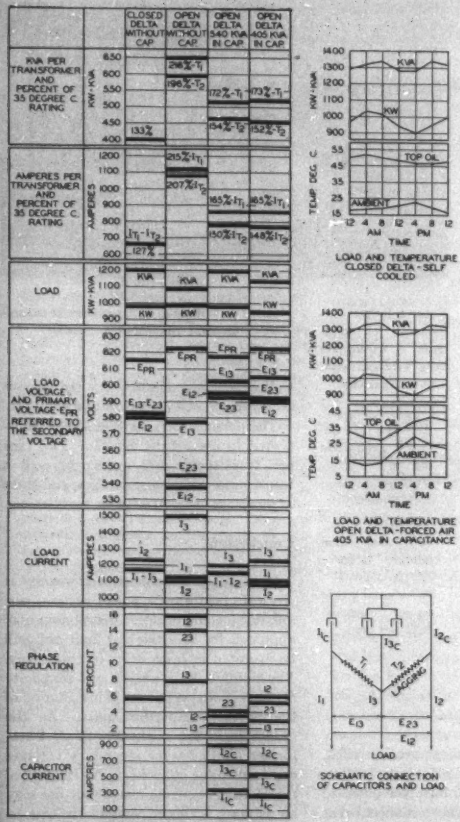


Figure 4. Performance of transformer bank in closed delta and in open delta with and without capacitors

Transformer rating:
300 kva, 35 degrees centigrade rise
Voltage: 40,000/575

Regulation:
100 per cent power factor—0.94 per cent
90 per cent power factor—3.70 per cent
80 per cent power factor—4.65 per cent

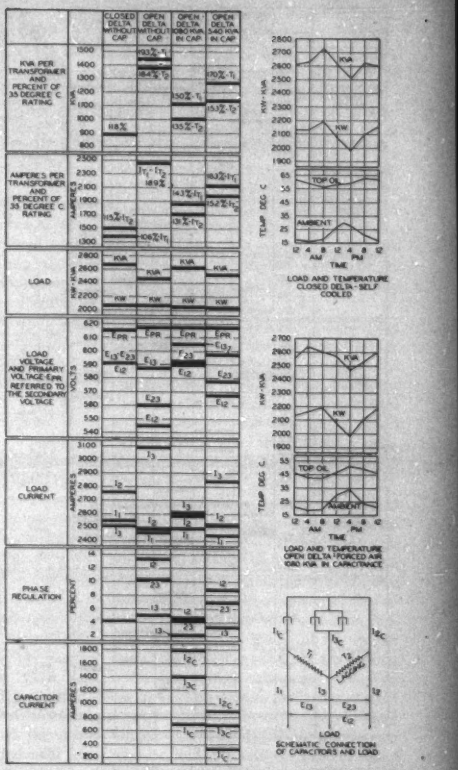


Figure 5. Performance of transformer bank in closed delta and in open delta with and without capacitors

Transformer rating:
750 kva, 35 degrees centigrade rise
Voltage: 44,000/600

Regulation:
100 per cent power factor—0.81 per cent
90 per cent power factor—2.73 per cent
80 per cent power factor—3.39 per cent

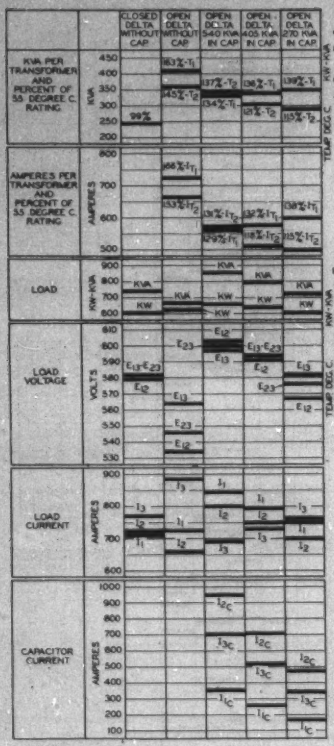
of 750 kva, 35 degrees centigrade, 44,000/575-volt transformers. In this case, capacitance of 1,080 kva was used for one set of readings and 540 kva for another, in each case the ratio of 2 to 1 across the lagging phase and open delta being retained. Figure 6 shows results with one 250-kva transformer of a bank of three out of service, a load of over 600 kw, with a normal power factor of approximately 80 per cent being carried by the remaining two transformers with a 540-kva capacitor unit. As in Figures 4 and 5, additional readings were taken with various amounts of capacitance.

The preceding figures illustrate the flexibility of the mobile capacitor units, for they are applicable to all open delta banks, regardless of primary voltage or impedance providing the secondary voltage is common to one of the two voltages for which these units are arranged. Provision is made to permit a portion of the 540 kva in each mobile unit to be disconnected quickly, still retaining the 2 to 1 ratio, if less capacitance is required for smaller loads, and, as shown in Figure 7, two or more units may be operated in parallel to take care of larger loads.

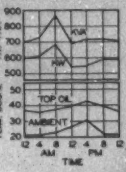
Description of Mobile Unit

As the total weight of the unit is only 4,600 pounds, it can be handled easily by car or light truck. Electric brakes are provided with brake control on a flexible cable, so each capacitor unit can be towed by any one of a number of vehicles.

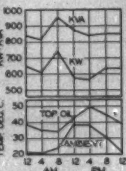
The enclosing housing is provided with doors on each side, one side providing access to a 50,000-kva automatic oil circuit breaker which controls the capacitor circuit. The door on the opposite side opens to a terminal board by means of which the capacitors may be grouped for either 600- or 2,400-volt operation. One multitap current transformer on each of the two groups of capacitors provides current indication and tripping energy.



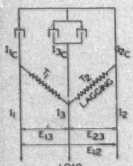
Ventilation of the capacitors and breaker is provided by openings in the bottom and at each side of the enclosing housing. Natural circulation of air was found insufficient to maintain capacitor temperatures within desired limits so a 12-inch exhaust fan was installed in one side of each mobile unit. This provided ample circulation for properly cooling the equipment.



LOAD AND TEMPERATURE CLOSED DELTA - SELF COOLED



LOAD AND TEMPERATURE OPEN DELTA - FORCED AIR. 540 KVA IN CAPACITANCE



SCHEMATIC CONNECTION OF CAPACITORS AND LOAD

The entrance bushings are stenciled, "Common," "High," and "Low," referring to the transformer bus; the phase to which the two transformers connect being the "Common," the phase having the higher voltage as referred to the "Common" connecting to the "High" terminal, and the remaining phase to the "Low" terminal. With this marking correct connection of the portable unit to the transformer bus can be made quickly.

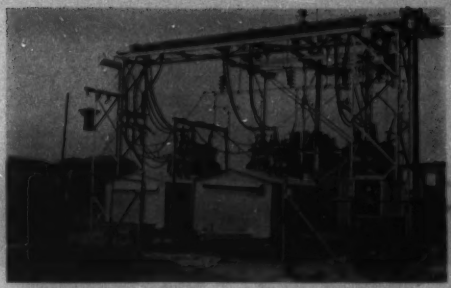


Figure 6 (left). Performance of open-delta transformer bank with and without capacitors

Transformer rating:
250 kva, 55 degrees centigrade rise
Voltage:
13,200/575

Regulation:
100 per cent power factor—1.2 per cent
80 per cent power factor—4.05 per cent

Figure 7. Test setup with two mobile capacitor units connected in parallel

Voltage readings are not required for correct connection if phase rotation is known

The portable fans can usually be transported in the towing vehicle. Two fans per transformer will ordinarily cool a transformer 500 kva or smaller, and three or more are used on a larger transformer.

Conclusion

By locating portable capacitor units at strategic points on a power system, permissible loading of closed delta banks may approach the safe thermal limit and still be operated in open delta in emergency. The mobility, light weight, and simplicity of connection, permit rapid installation of the portable capacitor units. As the mobile units are applicable to all transformer banks having secondary voltages common to the capacitors, the number of transformers held for emergency use may be reduced. This is particularly true on systems having a multiplicity of primary voltages.

Reference

1. A 100,000-Volt Portable Substation, Charles I. Burkholder and Nicholas Stahl. AIEE Transactions, volume 34, 1915, pages 279–92.

Equivalent Ambient Temperatures for Loading Transformers

W. C. SEALEY
MEMBER AIEE

Synopsis: Safe overloads for transformers can be determined by a modification of the American Standards Association rule for overloading to permit the use of an equivalent ambient temperature, which will result in the same loss of life as for continous operation at 30 degrees centigrade ambient and full load.

Based on the rule that aging of insulation doubles for each eight degrees centigrade increase in temperature, methods are developed for calculating the equivalent ambient temperature based on United States Government Weather-Bureau records. The equivalent ambient temperature for each month is calculated as the sum of the greatest recorded monthly mean temperature plus a daily correction factor based on the greatest recorded daily range, plus a monthly correction factor based on the greatest recorded monthly range. Monthly equivalent ambient temperatures so obtained can be used in combination with load curves to determine the permissible safe load for a transformer for a given locality.

Usefulness of Equivalent Ambient

TRANSFORMERS are given a name-plate rating in kilovolt-amperes which is the load they will carry under specified conditions. They may be safely overloaded beyond their name-plate rating under certain conditions, such as an ambient temperature below 30 degrees centigrade. In most locations ambient temperatures below 30 degrees centigrade exist for at least a portion of the time.

One method of conserving material is to utilize it to the best advantage so that greater output can be secured from a given quantity. Following these principles, transformers now in service can be used to carry loads greater than their name-plate rating, and new transformers with smaller name-plate ratings than the kilovolt-amperes to be carried can be secured for new applications.

Principles Governing Equivalent Ambient

Under normal operating conditions a transformer ages because of the effect of temperature in deteriorating the insulation. The rate at which the life of the insulation is consumed increases as the operating temperature is increased. An increase in ambient temperature of the cooling medium results in a corresponding increase in the operating temperature of the transformer and corresponding increased rate of loss of life. Similarly, a decrease in the ambient temperature results in a decrease in the rate of loss of life.

Under actual operating conditions, the ambient temperature varies continuously. According to the American Standards Association Guides for Operation "oil-immersed self-cooled transformers may be overloaded continuously one per cent of rated kilovolt-amperes for each degree centigrade that the daily temperature of the cooling medium is below 30 degrees centigrade."

Accordingly, if the transformer is operating at constant load throughout the year, the maximum load will be based on the hottest day of the year. The use of an equivalent ambient temperature permits fuller utilization of transformer capacity, taking advantage of the fact that operation at low temperatures at lower rate of loss of life tends to compensate for operation for a time at high temperatures with faster rate of loss of life of insulation.

The equivalent ambient temperature is defined as the temperature which, if maintained continuously during the period of time under consideration, would result in the same aging of insulation as that occurring under the actual ambient temperatures. The equivalent ambient temperature may be used with the following modification of the American Standards Association rule for overloading transformers: "For low ambient temperatures the continuous kilovolt-ampere loading may be increased one per cent for each degree centigrade that the equivalent ambient temperature is below 30 degrees centigrade for self-cooled transformers."

The calculations for determining the equivalent ambient temperature are based on the laws governing the aging of transformer insulation. If the rate of aging were proportional to the temperature, the equivalent temperature would be equal to the average temperature. Actually, however, aging proceeds more rapidly at higher temperatures. The rate of aging doubles for each increase in temperature of five to ten degrees centigrade. Figure 1 is a curve which shows the rate of loss of life as a function of operating temperature, assuming the rate of aging doubles for each increase in temperature of eight degrees centigrade. Since the rate of aging shown in Figure 1 is relative, the ordinates (degrees centigrade) can represent actual degrees centigrade or degrees centigrade above any assumed base temperature.

Where the ambient temperature changes slowly, it has the effect of increasing the operating temperature of the transformer a corresponding amount. For example, if the ambient temperature is 40 degrees centigrade instead of 30 degrees centigrade, the operating temperature of the transformer will be ten degrees higher.

The method of calculating the equivalent ambient temperature is illustrated by Figure 2. Curve *A* is the recorded ambient temperature plotted versus time. Using curve *A* as a base and the relation between temperature and rate of loss of life in Figure 1, curve *B* is plotted, representing the rate of loss of life in per cent of the rate of loss of life at ten degrees centigrade corresponding to points on curve *A*. The degrees centigrade of each point of curve *A* above the assumed base temperature of 10 degrees centigrade are used to find the relative rate of aging for that point from Figure 1, for plotting on curve *B* of Figure 2. The area under curve *B* represents the total loss of life, and the average value of the ordinates of curve *B* is the average rate of loss of life for the period considered. The equivalent ambient temperature is the sum of the base temperature of ten degrees centigrade plus the temperature from Figure 1 corresponding to the average loss of life in Figure 2, since, if maintained constantly, this temperature would result in the same total loss of life as results from curve *A*.

Integration in exactly this manner could be used for determination of the equivalent temperature.

However, when using available data, the problem is considerably simplified if the year is considered on a monthly basis and the characteristics of a typical day for each month are determined. The monthly equivalent ambient temperatures are obtained by combining the daily equivalent ambient temperatures for the days of the month. In turn, the

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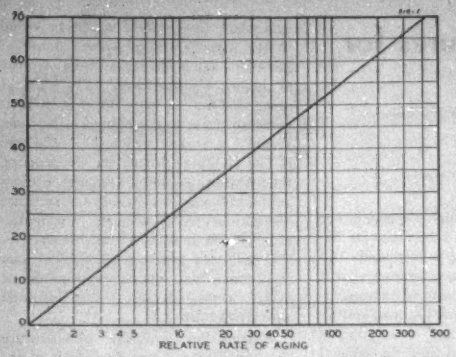

Figure 1 (left). Curve showing how rate of aging varies with the temperature according to the eight degrees centigrade rule

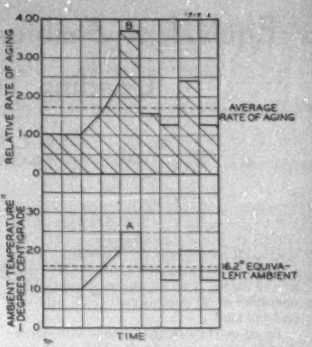

Figure 2 (right). Curves illustrating aging calculations

annual equivalent ambient temperature is obtained by combining the monthly equivalent ambient temperatures for the months of the year.

General Curves

Using the principle outlined in connection with Figures 1 and 2, it is possible to calculate the equivalent ambient for temperature variations with time for any shape of wave. A convenient manner of expressing the data so obtained is as a correction to be added to the average value of the wave or as a different correction to be subtracted from the maximum value of the wave. Curves showing the corrections to be added to the average value to obtain the equivalent temperature of a sine wave and of a wave in which the temperature varies as a straight line function of the time are shown in Figures 3 and 4. Figure 5 shows similar corrections to be subtracted from the maximum value of square top waves. These corrections in each case were obtained by calculating the equivalent temperature in the same manner as the equivalent temperature of Figure 2 was obtained.

Daily Temperatures

The records of the weather bureau for the location considered can be used to determine average daily temperatures and the variation during the day of the hourly temperature.

Transformers do not respond immediately to changes in ambient temperature because of the thermal capacity of their copper, iron, and oil. The effect of the thermal capacity of a transformer is twofold. It tends to smooth out and average the effect of rapid changes in temperature. In addition, it decreases the effect of the change so that a change of ten degrees in ambient during a 24-hour period, for example, will result in only an eight-degree change in the hot-spot temperature of the transformer. The mathematical relations governing this effect are derived in Appendix I where it is shown that the variation in temperature of a typical transformer caused by sine-wave variation in the ambient temperature during one day is 80 per cent of the ambient-temperature variation. The effect of the higher harmonics is smoothed out and decreased more than the temperature variation because of the fundamental frequency of one cycle per day.

Figure 6 shows typical daily variation in temperatures taken from reports of the United States Weather Bureau. This curve is of the general form of a sine wave with superimposed higher frequency harmonics of smaller magnitude.

The daily range in temperature may vary from a few degrees to as much as 50 degrees Fahrenheit or more. An examination of weather-bureau records of the range in temperatures indicates that the greater ranges may occur in connection with the highest temperature of the month or with the lowest or intermediate temperatures. Consequently, the assumption is made that every day has the same daily range in temperature. It will be noted that curve *A* of Figures 3 and 4 gives practically the same results as taking 80 per cent of the range and applying it to curve *B*. Consequently, for correcting for daily range the correction from curve *A* corresponding to the daily range may be added to the average temperature. The value of daily range to be chosen depends upon the conservatism desired. In order to insure conservative values of ambient temperature, the use of the greatest recorded daily range in temperature is recommended.

(The American Standards Association rule takes into account daily variations, and strictly speaking no correction would be made for them. However, in the interest of greater exactness, it seems logical to make this correction in order to obtain a constant base for the life of insulation instead of a varying base depending upon the locality.)

Monthly Temperatures

If the mean daily temperatures are averaged over a period of years, the average daily temperatures will vary with time in accordance with a sine wave. Figure 7 shows values for Milwaukee over a period of 55 years. The average maximum, the average mean, and the average minimum daily temperatures vary as sine waves with superimposed higher harmonics of smaller magnitude.

On the average the temperature during an individual month will follow a portion of a sine wave. Since there are 12 months

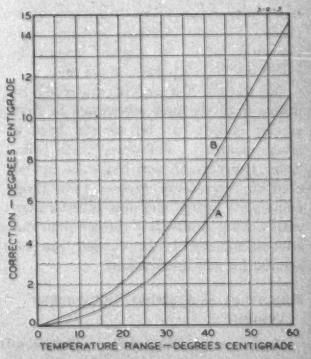

Figure 3. Correction curves—degrees centigrade

Curve *A*—Correction to be added to average value of straight-line variation of temperature to obtain equivalent temperature

Curve *B*—Correction to be added to average value of sine wave of temperature to obtain equivalent temperature

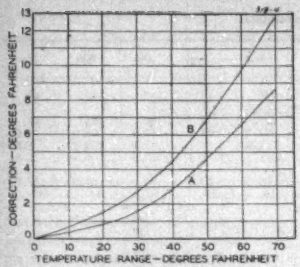

Figure 4. Correction curves—degrees Fahrenheit

Curve *A*—Correction to be added to average value of straight-line variation of temperature to obtain equivalent temperature

Curve *B*—Correction to be added to average value of sine wave of temperature to obtain equivalent temperature

in a year, and the period of yearly variation of temperature is 12 months, each month will extend over $^1/_{12}$ of 360 degrees, or 30 degrees. Since the curvature of each part of a sine wave is different, the actual shape of the ideal monthly variation will be different for each period of the year. If a straight line is drawn through the maximum value for the month and the average value for the month, a very close approximation will be obtained for periods of the order of one month. The portion of the curve which has the greatest effect on the aging is the portion above the average value, and it will be apparent by inspection of the straight lines *A*, *B*, and *C* of Figure 8 that very little error is introduced by assuming a straight-line variation of temperature with time during a month, if the straight line passes through the maximum value of temperature and the mean value of temperature located at the halfway point of the month. Figure 9 shows typical values of the variation of daily temperature during the month. The mean temperatures plotted are arranged in their order of magnitude with the hottest day plotted at the left and progressing to the coldest day at the right. These curves are in accordance with the ideal variation in that a straight line drawn through the maximum daily mean temperature for the month and the monthly mean temperature results in a very good approximation of the monthly equivalent. Consequently, curve *A* of Figures 3 and 4 can be used to obtain the correction for variation of daily mean temperatures during the month. The range in temperatures to be used depends upon the conservatism desired. In order to insure conservative values of ambient temperature, the use of the greatest monthly range of daily mean temperatures ever recorded for that month is recommended. This figure is not always readily available. In such cases one of the other approximations given in Appendix III can be used.

Figure 10 shows a nontypical variation of temperatures during a month in which the temperatures vary considerably from a straight line. However, even here the straight line drawn through the maximum and the mean temperatures represents an equivalent temperature that is not greatly in error, and such a wave shape is certain to have an average value that is lower than the greatest average value ever recorded for the month, because of the effect of the low values in reducing the average. This is illustrated by the figure where the actual mean was 20 degrees Fahrenheit for the month and greatest mean recorded for that month is 34 degrees Fahrenheit.

Reports of the weather bureau show the mean temperature for each month over a large number of years. By selecting the greatest mean temperature which has been recorded for that month, a value of average temperature is obtained which is not likely to be exceeded in the future years or in any case by more than a small amount. Using these values, the equivalent monthly ambient is equal to the greatest mean temperature ever recorded for the month, plus the daily correction corresponding to the greatest daily range ever recorded for the month from curve *A* of Figures 3 or 4 plus the monthly correction corresponding to the greatest monthly range in daily mean temperature ever recorded for the month from curve *A* of Figures 3 or 4.

After equivalent temperatures for each of the 12 months of the year have been calculated, the equivalent temperature for any period of time involving two or more months can be determined readily by use of Figure 5. By successively combining months, the equivalent temperature for the complete year may be obtained with accuracy, without making assumptions as to the variation of the average monthly temperatures throughout the year.

Source of Data

The most convenient source of temperature data to be used in calculating the equivalent ambient is the annual and monthly meteorological summaries of the location concerned which can be obtained in each case from the local weather bureau. A list is given in Appendix II of the cities which have United States Weather Bureaus which issue meteorological summaries. In addition, weather bureaus can furnish certain specific data on request. An example of such data is the greatest daily range in temperature which has ever occurred during a given month since an early date.

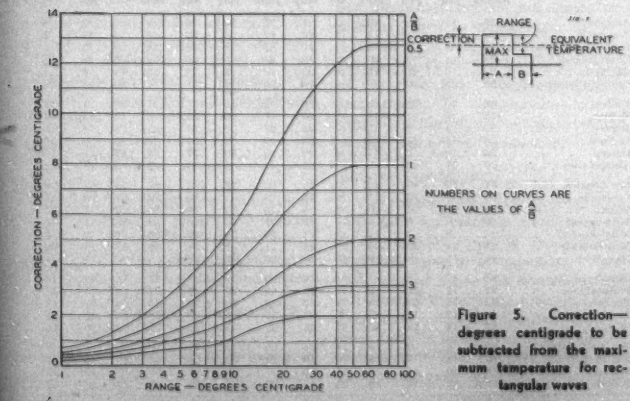

Figure 5. Correction—degrees centigrade to be subtracted from the maximum temperature for rectangular waves

Recommended Rules for Calculating Equivalent Ambient

1. The daily correction is read from curve *A*, Figure 3 or 4, corresponding to the value of the greatest recorded daily range in temperatures for the month.

2. The monthly correction is read from curve *A*, Figure 3 or 4, corresponding to the greatest recorded range of daily mean temperatures for the month. (See appendix for approximations.)

3. The equivalent monthly temperature equals the maximum mean temperature for the month considered, for any year plus the

Table I. Typical Calculation of Equivalent Ambient Temperatures

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Greatest daily range	36	44	46	40	39	34	29	30	42	33	43	43
Greatest monthly range in daily temperature	49	51	50	44	39	34	30	27	34	40	51	46
Greatest monthly mean	46.2	42.2	52.5	59.2	67.9	78	80.6	79.2	75.4	62.8	50.9	44.6
Daily correction	2.3	3.5	3.8	2.8	2.7	2.0	1.5	1.6	3.1	1.9	3.3	3.3
Monthly correction	4.4	4.8	4.6	3.5	2.7	2.0	1.6	1.3	2.0	2.8	4.8	3.8
Equivalent ambient (degrees Fahrenheit)	52.9	50.5	80.9	65.5	73.3	82.0	83.7	82.1	80.5	67.5	59.0	51.7
Equivalent ambient (degrees centigrade)	12	10	16	19	23	28	29	28	27	20	15	11
	11.1		17.6		25.8		28.5		24.1		13.2	
	14.9				27.2				20			
			22.7						20			
				21.9								
	11.1		19.6			28.3			20			
C		16.8				28.3			20			
Permissible per cent overload C		13.2				1.7			10			
Equivalent ambient—D		15.9				28.3			24.1		15.9	
Permissible per cent overload D		14.1				1.7			5.9		14.1	

daily correction from rule 1 plus the monthly correction from rule 2.

4. The equivalent temperatures for periods of two or more months may be obtained by combining equivalent monthly temperatures using the curves of Figure 5 and subtracting the correction of Figure 5 from the higher equivalent ambient monthly temperature.

Application of Rules for Calculation of Equivalent Ambient

Table I shows how these rules may be applied to calculating equivalent ambient temperature by their application to the Philadelphia district. The data were obtained from the local weather bureau. The first three lines of Table I contain data obtained from the weather bureau in Philadelphia. The fourth and fifth lines are the daily and monthly corrections from Figure 4 corresponding to the temperature ranges in lines 1 and 2, respectively. The equivalent ambient (degrees Fahrenheit) is the sum of the preceding three lines. The equivalent ambient in degrees Fahrenheit is converted into degrees centigrade. In the following lines, the months are combined into longer periods, using the curves of Figure 5. The period considered is represented by the arrows. The equivalent yearly ambient is 21.9 degrees centigrade. According to the modification of the American Standards Association rule, a transformer can carry 30–21.9 or 8.1 per cent additional load continuously in this locality; that is, a load of 108 per

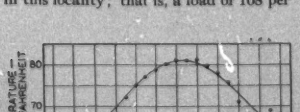

Figure 6. Typical variation of ambient temperature during 24-hour period

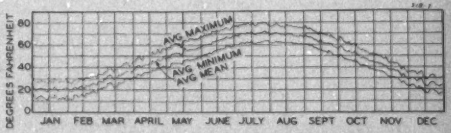

Figure 7. Typical variation of average daily temperatures over a period of 55 years

cent of the name-plate rating. This is shown by curve *C* of Figure 11. Curves *A* and *B* are determined similarly.

Application of Equivalent Ambients to Load Curves

Any yearly load curve can be plotted in per cent of the maximum load as shown by Figure 12, curve *B*. By plotting the permissible load for the same periods of time as the load blocks on the same scale, an indication will be obtained as to which curve best fits the load scale. In some cases a recombination of curves will allow the load curve to be approached more closely. It should be noted that only one of the safe load curves may be used. That is, any curve has the same loss of life as any other curve, but it is not permissible to use part of one curve for a portion of the year and part of another curve for another portion of the year. It is, of course, permissible to divide the permissible load curves into blocks of uneven periods of time, as is shown by curve *C* of Figure 12. This is accomplished by the use of the curves of Figure 5 in connection with the equivalent monthly ambient temperatures.

Example. Assume the maximum kilovolt-amperes of load curve *B* of Figure 12 is 8,000 at 80 per cent daily

Table II. Equivalent Ambient Temperatures (Degrees Centigrade) for Various Localities

	Annual	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Atlanta	25	16	17	20	23	27	30	30	30	31	25	20	18
Bismarck	21	3	8	14	17	23	27	32	28	25	19	11	7
Boston	20	8	7	11	15	22	27	28	26	24	20	13	11
Chattanooga	24	16	17	20	22	26	30	30	30	28	25	20	16
Chicago	21	10	10	13	18	23	28	28	27	25	19	14	11
Corpus Christi	28	22	22	25	27	28	30	31	31	30	29	25	24
Dallas	28	25	20	23	26	28	32	33	33	31	26	21	18
Denver	23	12	13	15	19	23	27	30	31	26	20	15	14
Detroit	20	6	8	11	17	23	27	28	27	25	18	13	8
El Paso	26	15	15	20	24	28	32	32	31	30	25	20	16
Helena	20	10	8	11	16	20	25	29	27	22	17	11	10
Kansas City	25	11	13	20	21	26	32	33	33	28	22	18	13
Los Angeles	24	20	20	22	22	23	25	27	27	27	25	23	20
Louisville	24	16	13	18	22	26	28	31	30	29	22	20	17
Miami	28	27	25	26	28	28	29	30	30	29	28	27	27
Milwaukee	20	6	6	10	16	21	27	28	26	23	18	13	7
Minneapolis	21	2	3	12	18	24	28	30	29	24	18	9	6
New Orleans	27	23	23	24	25	28	31	31	31	30	29	23	22
New York	21	11	9	14	18	23	28	29	27	26	20	14	11
Oklahoma City	25	17	19	21	23	26	32	32	33	31	26	20	13
Philadelphia	22	12	10	16	19	23	28	29	28	27	20	15	11
Phoenix	31	18	20	23	28	32	36	39	38	35	30	22	18
Pittsburgh	23	12	12	15	20	25	27	30	29	26	21	17	12
St. Louis	25	14	13	20	22	26	32	33	32	27	22	20	15
Salt Lake City	22	6	9	13	18	24	29	32	31	26	19	11	8
San Francisco	19	14	15	18	19	20	21	20	20	22	20	18	14
Seattle	18	10	11	16	17	20	21	23	22	20	17	12	10
Washington, D. C.	23	12	13	18	21	26	28	31	30	28	21	16	13

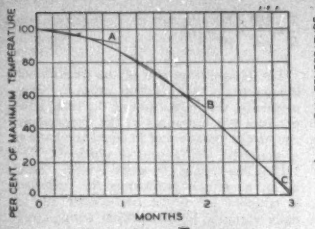

Figure 8. Comparison of assumed straight lines with ideal sine waves for variation during a monthly period throughout the year

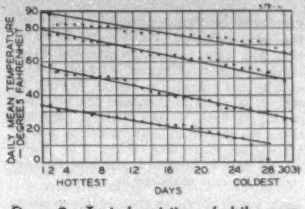

Figure 9. Typical variation of daily mean temperatures during a month arranged in the order of magnitude for four different months

The straight lines are drawn through the maximum and the mean temperature points

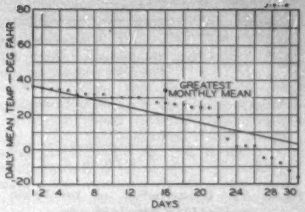

Figure 10. Nontypical variation of daily mean temperature during a month

load factor. The location is Philadelphia. The correction for load factor is six per cent according to the interim report on transformer overloading and its effect is considered separately. Curves *A* and *C* are calculated as shown on Table I. If the unit is loaded by curve *A*, it will be noted that curves *A* and *B* are closest from January to April. Consequently, the transformer kilovolt-amperes required will be

$$\frac{8{,}000}{1.08} = 7{,}400 \text{ kva}$$

If curve *C* is used, the transformer kilovolt-amperes required is 8,000/1.13 = 7,070 kva. An examination of Table I shows that the equivalent ambient for November and December is lower than for the critical period, January to May. Consequently, greater overloads can be carried during the critical period if November and December are added to the block of the critical period to obtain curve *D* of Figure 12. If curve *D* is used, the transformer kilovolt-amperes required is

$$\frac{8{,}000}{1.14} = 7{,}020 \text{ kva}$$

The ordinates of curve *B'* are equal to the ordinates of curve *B* multiplied by 8,000/7,020. A still further correction of six per cent can be made for the load factor so that the transformer kilovolt-amperes required =

$$\frac{7{,}020}{1.06} = 6{,}620 \text{ kva}$$

That is, 6,620 transformer kilovolt-amperes is required to supply a maximum load of 8,000 kva, which varies during the year in accordance with load curve *B* with an 80 per cent daily load factor.

Equivalent Ambient Temperatures for Various Localities

Table II shows calculated values of monthly and annual equivalent ambient temperatures for various localities in the United States. These values can be used for calculating permissible overloads for transformers.

By reference to this table, it will be noted that there is much greater variation in winter monthly ambient temperatures among localities than there is variation in the annual ambient temperatures or summer ambient temperatures. For example, during January the variation is from two degrees centigrade for Minneapolis to 25 degrees centigrade for Dallas, compared to an annual variation of from 20 degrees centigrade for Boston to 31 degrees centigrade for Phoenix. During July the variation is only from 28 degrees centigrade for Boston to 39 degrees centigrade for Phoenix and 33 degrees centigrade for Dallas. By the eight-degree rule, the higher temperatures which occur have a much greater effect on the value of the equivalent ambient than the lower temperatures. The variation among localities of the highest temperatures is less than the variation among localities of the lowest temperatures. Consequently, the greatest variation among localities in safe loads will be during the winter months, not during the summer nor on an annual basis.

These facts, in combination with the example in Table I, illustrate the value of using monthly equivalent ambient temperatures in combination with a yearly load curve for obtaining maximum output from a given transformer.

Accuracy of Method

The greatest values ever recorded have been used for monthly mean temperatures, monthly range in temperatures, and daily range in temperatures. Typically shaped curves for the manner of variation of temperature with time have been used. The eight-degree rule has been assumed for the variation of the life of insulation. The life base used is that of a transformer operated continuously at full load and 30 degrees centigrade ambient.

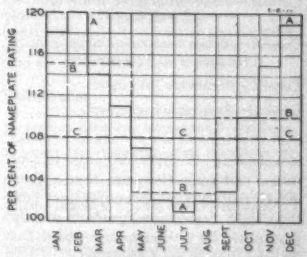

Figure 11. Safe overload curves for Philadelphia

Curve *A*—Monthly curve
Curve *B*—Curve in four month blocks
Curve *C*—Constant load curve

For most years the actual values of every one of the factors of mean temperature and ranges will be less than the values assumed. In addition, if one factor is low, it will tend to compensate for higher values of other factors. Consequently, the loss of life in nearly all years will be considerably less than the assumed value. The fact that low loss of life in one year will offset a high loss of life in another year provides an additional factor of safety. Such conservative relations are desirable, since, if the equivalent ambient is to be safe for any year, it must be safe for the worst year which is liable to occur.

It is, of course, possible to have an unusual combination of mean temperature, temperature ranges, and shape of variation curves such as to produce a higher loss of life in a month than the base value, but such an occurrence is extremely unlikely. However, should such a combination occur, its effect will be to exceed the base by only a small amount and very infrequently, and therefore it can be considered in the same class as an emergency overload.

The eight-degree rule has been found to be approximately correct by several

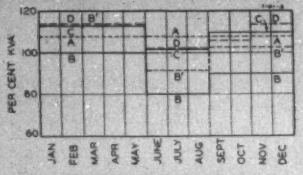

Figure 12. Determination of permissible overload for a given load curve

Curve *A*—Permissible constant load curve

Curve *B*—Actual load curve in per cent of maximum load

Curve *B'*—Actual load curve in per cent of transformer kilovolt-amperes

Curve *C*—Permissible load curve

Curve *D*—Permissible load curve

independent investigators at various times, and indications are that a five-degree rule or a lower-temperature rule than eight degrees centigrade is unduly pessimistic for a transformer which has its insulation in good condition.

Conclusions

1. The use of equivalent ambient temperatures permits the load capacity of transformers to be utilized more fully, so that greater loads may be carried on present transformers, or so that smaller transformers may be secured for a given load.

2. The equivalent ambient temperature can be calculated from the records of the local weather bureau, as the monthly mean temperature plus a correction for daily range in temperature plus a correction for a monthly range in temperature.

3. Values of equivalent ambient temperatures which permit overloads to be carried with demonstrable safety can be obtained.

4. The rules given in the text permit the determination of the equivalent ambient temperatures and corresponding overloads with a limited amount of calculation.

5. The monthly equivalent ambient temperatures for each month of the year and combinations of them are more generally useful than the annual equivalent ambient for determining permissible overloads on transformers.

Appendix I. Effect of the Thermal Capacity of a Transformer in Modifying Daily Temperature Variation

In the portion of the heat circuit shown in Figure 13, heat is assumed to be flowing from point *A* to point *B* through the heat-resistive material (shown shaded) with a resistance *R* where *R* equals the temperature difference required to cause one watt of power to flow through the thermal circuit under steady conditions. Let the thermal capacity be *K*, where *K* is the watt-hours per degree centigrade thermal capacity of the body considered. Let *W* equal the watts heat flow from *A* to *B*, *t* = time and T_x = the temperature difference between *A* and *C*. In this circuit the energy flowing in time *dt* is equal to *W dt*, and the heat absorbed is equal to the thermal capacity times the change in temperature or $K dT_x$. (T_x = temperature drop across *K*.) Since all the heat is absorbed, the heat flowing equals the heat absorbed or

$$W dt = K dT_x$$

Solving for T_x,

$$T_x = \frac{1}{K} \int W dt$$

The temperature drop across the resistance *R* is equal to *RW*. Therefore, the total temperature drop in the circuit is equal to

$$T = RW + \frac{1}{K} \int W dt$$

The equation of an electric circuit containing resistance and capacitance only is given as follows:

$$e = rI + \frac{1}{C} \int I dt$$

By inspection, it is evident that *T* in the equation corresponds to *e*, *R* corresponds to *r*, W corresponds to *I*, and *K* corresponds to *C*. It is evident that thermal capacity bears the same relation to the heat circuit that the electrical capacity has in the electric circuit.

Figure 13. Heat circuit and analogous electric circuit

The reactance to heat flow = *X*, and, by analogy to the electric circuit, is equal to $1/2\pi fK$, where *f* = the frequency. For a typical transformer with a 45 degrees centigrade oil rise for continuous operation, a thermal time constant of three hours, and a watts loss of *W*, the resistance to heat flow in the circuit, $R = 45/W$.

Normally, the ambient temperature of a transformer varies according to a daily cycle with a high point during the day and a minimum during the night, according to a sine law with sometimes superimposed higher-frequency variations (Figure 4). Consequently, *f* can be assumed to be = 1/24 cycles per hour.

The thermal time constant is the time required to reach the ultimate temperature, if all heat were absorbed by the thermal capacity of the transformer. Consequently, for a typical transformer when the thermal time constant is 3, the value of

$$K = \frac{W \times 3}{45} = \frac{W}{15}$$

$$X = \frac{1}{2\pi fK} = \frac{1}{2\pi \times \frac{1}{24} \times \frac{W}{15}} = \frac{180}{\pi W}$$

$$\frac{X}{R} = \frac{180}{\pi W} \times \frac{W}{45} = 1.27$$

The temperature rise of the transformer is equal to the thermal drop across *X*. Consequently, the proportion of the total temperature which appears as the temperature rise of the transformer is equal to the sine of the angle, the tangent of which = X/R = 1.27. The sine of the angle = 0.79. That is, for a typical transformer the variation in temperature of the transformer due to daily variation in the ambient temperature is 80 per cent of the ambient variation.

Appendix II. Locations of Government Weather Bureaus from Which Meteorological Summaries May Be Obtained

ALABAMA
Birmingham
Mobile
Montgomery

ARIZONA
Flagstaff
Phoenix
Yuma

ARKANSAS
Fort Smith
Little Rock

CALIFORNIA
Eureka
Fresno
Los Angeles
Redding
Sacramento
San Diego
San Francisco

COLORADO
Denver
Grand Junction
Pueblo

CONNECTICUT
Hartford

DELAWARE
Delaware Breakwater

DISTRICT OF COLUMBIA
Washington

FLORIDA
Apalachicola
Jacksonville
Key West
Miami
Tampa

GEORGIA
Atlanta
Augusta
Macon
Savannah

IDAHO
Boise
Pocatello

ILLINOIS
Chicago
Peoria
Springfield

INDIANA
Evansville
Fort Wayne
Indianapolis

IOWA
Charles City
Davenport
Des Moines
Dubuque
Sioux City

KANSAS
Concordia
Dodge City
Kansas City
Topeka
Wichita

KENTUCKY
Louisville
Pikeville

LOUISIANA
New Orleans
Shreveport

MAINE
Eastport
Portland

MASSACHUSETTS
Boston

MICHIGAN
Alpena
Detroit
Escanaba
Grand Rapids
Houghton
Marquette

MINNESOTA
Duluth
Minneapolis

MISSISSIPPI
Meridan
Vicksburg

MISSOURI
Columbia
Kansas City
St. Joseph
St. Louis
Springfield

MONTANA
Billings
Havre
Helena
Kalispell
Miles City

NEBRASKA
Lincoln
North Platte
Omaha
Valentine

NEVADA
Reno
Tonopah
Winnemucca

NEW HAMPSHIRE
Concord

NEW JERSEY
Atlantic City

NEW MEXICO
Albuquerque
Roswell

NEW YORK
Albany
Buffalo
Canton
New York
Rochester
Syracuse

NORTH CAROLINA
Asheville
Charlotte
Hatteras
Raleigh

NORTH DAKOTA
Bismarck
Devils Lake
Fargo
Williston

OHIO
Cincinnati
Cleveland
Columbus
Toledo

OKLAHOMA
Oklahoma City

OREGON
Portland
Roseburg

PENNSYLVANIA
Erie
Harrisburg
Philadelphia
Pittsburgh

SOUTH CAROLINA
Columbia
Charleston

SOUTH DAKOTA
Huron
Rapid City

TENNESSEE
Chattanooga
Knoxville
Nashville

TEXAS
Abilene
Amarillo
Austin
Brownsville
Corpus Christi
Del Rio
Dallas
El Paso
Fort Worth
Galveston
Houston
San Antonio

UTAH
Salt Lake City

VERMONT
Burlington

VIRGINIA
Lynchburg
Norfolk
Richmond

WASHINGTON
Seattle
Spokane
Walla Walla

WEST VIRGINIA
Columbia
Charleston

WISCONSIN
Green Bay
La Crosse
Madison
Milwaukee

WYOMING
Cheyenne
Lander
Sheridan
Yellowstone Park

Appendix III

In many cases local weather bureaus have compiled from their records values of the greatest range in daily mean temperature during each month in any one year. When this figure is not available, some other approximation of the monthly range may be used in its place. One convenient base for such an estimate is the greatest daily range ever recorded during the month. An examination of temperature records will show that the greatest range in monthly mean temperature is approximately the same as the greatest recorded daily range for the month. The correlation is not accidental. If the phenomena concerned are investigated, it will be apparent that large daily changes are due to changes in the wind direction from a cooler region to a warmer region or vice versa combined with the effect of sunshine and precipitation, both factors being reduced in effect by the thermal capacity of the earth. Monthly variations are due to the same causes, and a correlation between the variation of daily mean temperature during the month and the maximum variation of temperatures during the day would be expected. For calculation several alternatives are possible: 1. To assume that the monthly range of daily mean temperature is equal to the greatest daily range for that month. 2. More conservatively, the monthly range may be assumed to be equal to the greatest daily range ever recorded for that locality. Still another approximation for the monthly range may be based on the greatest daily mean temperature ever recorded in that month and the greatest monthly mean temperature ever recorded for that month. Twice the difference of these two values may be used as the value of the monthly variation.

It is obvious that the value of the equivalent ambient temperature obtained will be different, depending upon which one of these approximations is used. However, the difference will not be great, and the overloads obtained will be reasonably safe. The more conservative the figure used for the monthly variation, the less frequent will be overloads combined with ambient temperatures which must be classed as emergency conditions. The life of the transformer will be prolonged if emergency conditions occur with less frequency. The safest practice is, of course, to use the most conservative of the methods in cases where data for different methods are available.

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Wood-Pole 230-Kv Transmission Lines

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MEMBER AIEE

STEEL has been comparatively cheap in the United States and, until recently, available in quantity. Consequently the use of steel structures for supporting the higher-voltage transmission lines has been favored by transmission engineers. However, since conservation of critical materials has become necessary, it is essential that designs incorporating wood construction be considered for such applications. A contribution to efforts in this direction is provided by a review of the design used for single-circuit wood-pole 230-kv transmission lines recently constructed to supply power to an important industrial area.

Early in 1942 plans for this project, including steel-tower designs, had been completed, and materials were about to be ordered when restrictions regarding the use of steel became effective. Subsequently, the project was redesigned for wood-pole construction, and the entire project consisting of 158 miles of single-circuit 230-kv line was completed and placed in operation 5½ months later.

The decision to use wood construction precipitated a hasty review of previous experience with such designs. It was found that wood-pole construction had been used in Sweden for 230-kv operation with satisfactory results. However, detailed information regarding these lines was not available. These lines are the longest wood-pole lines built in the United States for 230-kv operation and the only ones for which wood has been used for all structures and all types of structures.

Design Premises

Conventional designs for transmission lines operating at lower voltages were available, and many had been proved satisfactory over long periods of operation. The general form of the two-pole *H*-frame structure appeared acceptable, though it was found that the problem of design was increased greatly because of increased insulation and conductor-clearance requirements, greater mechanical loads caused by the increased conductor diameters, and correspondingly increased ice and transverse wind loads. It was intended that the lines should be designed to operate with a high degree of reliability and that high factors of safety should be employed in consideration of the importance of the connected load and the complete lack of previous experience with wood-pole construction for 230-kv operation. To attain high electrical reliability, advantage was taken of the insulating value of the wood supporting members in the paths between conductors and ground. Suspension insulator strings of 15 5¾-inch units were provided, and these were supported through large metallic surfaces in order to distribute leakage currents. Experimental data regarding the minimum insulation required for 230-kv operation to prevent digestion and burning of crossarm material were not available. Operating records of lower-voltage wood-pole lines with proportionately less porcelain insulation indicate that the number of insulator units selected for these lines will assure satisfactory performance.

The impulse flashover voltage (1½ x 40-microsecond negative wave) of a 15-unit insulator string is 1,345 kv, which is the flashover voltage of a rod gap of 76 inches. The minimum clearance of the conductor from the pole ground wire was maintained at 86 inches. This value of minimum clearance permitted a maximum conductor displacement of 37.5 degrees from vertical. Minimum clearance to crossarms and other wooden members was 76 inches. For determinations of maximum conductor displacement, a wind pressure of eight pounds per square foot on bare conductor was assumed.

Crossarm Design

The length of crossarm required to maintain clearance desired under these conditions was 50 feet, which length provided a conductor separation of 24 feet. Each crossarm consisted of 3- by 12-inch timbers, two 28-foot lengths and two 22-foot lengths, spliced at the center by means of a block 10 feet long and 12 by 7¼ inches in cross section. A lapped joint was designed using bolts and split-ring timber connectors between surfaces in contact. Blocks of similar dimensions except four feet in length, were installed between the 3- by 12-inch members at the ends of the crossarm, also by means of bolts and timber connectors. These blocks served to increase greatly the strength of the arm in the longitudinal direction.

Conductors

Hollow copper conductors of 500,000 circular mils cross section, 1.1 inches in diameter, were installed. The conductor loading assumed was one-half-inch radial ice with an eight-pound wind at zero degrees Fahrenheit. The maximum tension under this loading condition is 9,000 pounds or 41.5 per cent of the ultimate strength. Two overhead ground wires, each consisting of three number 5 extra-high-strength copper-covered steel strands, were installed and located so as to provide 30-degree angles of protection for each conductor. The maximum tension of overhead ground conductors is 4,300 pounds or 36 per cent of the ultimate strength.

Structure Design

To meet National Electric Safety Code requirements for grade-*B* construction and to provide sufficient strength for spans of reasonable length, class-2 poles were specified and installed. Poles 65 feet in length were required in order to provide level ground spans of 520 feet and the desired final clearances of conductors to ground of 32 feet at 60 degrees Fahrenheit. The pole-market situation early in 1942, however, was such that 65-foot poles were not available in the necessary quantities, though relatively greater quantities of 60-foot class-2 western-red-cedar, southern-pine, and Douglas-fir poles were available for early shipment. Poles 60 feet in length were purchased and were made to serve the purposes of 65-foot poles by installing latticed steel-channel extensions on the tops of each of the poles of the two-pole structures.

The top of the steel-pole extension and the end of the crossarm were connected through a tension member, and the tops of the extensions were in turn tied together by means of one-half-inch Siemens-Martin strand. Formed channel bayonets were bolted to the steel-pole extensions to support the overhead ground wires.

The structure was strengthened by means of a *K*-brace assembly consisting of 3- by 10-inch timbers and 3- by 6-inch timbers, and an *X*-brace consisting of two

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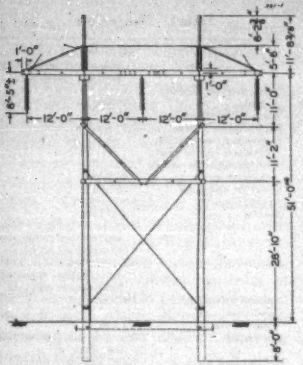

Figure 1. Type-*A* tangent structure

one-half-inch Siemens-Martin strands in the lower section. Each joint was carefully designed and assembled with bolts and timber connectors in an effort to attain complete rigidity of the structure in the direction of transverse wind loads.

Structure Types

Two circuits were built on a single right of way 250 feet in width, and center lines of structures of the two circuits were spaced 100 feet. Guying was so arranged that all guy stub poles and anchors were within the limits of the right of way.

The type-*A* tangent structure, shown in Figure 1, was installed at all normal tangent positions in the line and for small angle positions, guyed and unguyed, depending upon the angles of the line. The maximum angle with which this type of structure could be used was approximately three degrees. The point of minimum strength in the type-*A* structure is at the upper point of connection of the *K*-brace to the pole. For this reason, additional strength could not be obtained by guying from this point or from points lower on the structures. Therefore, guying at slight angles was accomplished by connecting to the end of the crossarm and extending the guy horizontally to a stub pole, then to the anchor connection at the usual angle. A wood strain insulator was installed in the horizontal guy between the crossarm and the stub pole in order to maintain the insulation level of the line. To provide transverse support for the overhead ground wires, a second guy was connected to the overhead ground-wire attachment on the bayonet. The two bayonets were connected horizontally by means of one-half-inch Siemens-Martin strand. Since pole ground wires were not installed on poles of guyed structures of any type, the overhead ground wires were connected to earth at such structure locations by means of the guy strands and anchor rods. Guys for type-*A* structures were installed on one side for small angles in the line and, similarly, on both sides for structures supporting long spans.

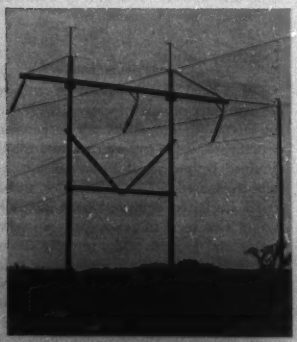

Figure 2. Type-*B* angle structure

The type-*B* structure, shown in Figure 2, is a variant of the type *A* in that the crossarm was offset two feet, and angle brackets were added in order to provide desired conductor clearances at angles in the line up to approximately eight degrees. Type-*A* structures were guyed also in the same manner as shown in this illustration. In relatively level sections of the right of way type-*A* and type-*B* structures were assembled on the ground and erected by means of special equipment shown in Figure 6. In rugged and hilly sections the use of this equipment was not feasible or economical. In these sections arms, braces, and all fittings were installed by means of hoisting equipment after poles had been installed.

The type-*C* structure, shown in Figure 3, is a braced and guyed angle suspension structure and was installed at positions where the line angle was between approximately 8 degrees and 25 degrees. The type-*C* structure is conventional, though enlarged for 230-kv operation, except that 12,000-pound wood strain insulators were installed as tension members to transmit overturning stresses from the tops of the unguyed poles to the guys.

Dead-end structures, referred to as type *D*, and shown in Figure 4, were installed for long spans, at line terminals, and at locations where the line angle exceeded approximately 25 degrees. At angle positions guys of sufficient strength to withstand maximum tensions of conductors and overhead ground wires were installed on both sides of the structures and in line with conductors and overhead ground wires, except that the overhead ground wire inside the angle at such positions was installed in suspension and held in place by one guy to the top of the guyed pole at the opposite side of the structure. This was done to avoid the use of stub poles and overhead guys. At tangent locations conductors were guyed in the same manner. In order to maintain clearances between conductors and overhead ground-wire guys at tangent locations, guys were installed in vertical planes displaced 45 degrees from the vertical planes of the conductors, and pole tops were connected together by means of one-half-inch Siemens-Martin strand in order to balance guying stresses.

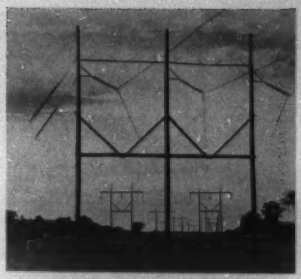

Figure 3. Type-*C* angle structure

Two sets of transposition structures were installed in each circuit to provide one complete barrel to balance the electrical characteristics of the three phases. Type-*F* structures were installed for this purpose, and are as shown in Figure 5.

At two locations it was necessary to cross high-voltage tower transmission lines of the power company operating in the area in which these lines were built. Crossing spans were supported in each case by type-*A* structures using 100-,

Figure 4. Type-*D* dead-end structure

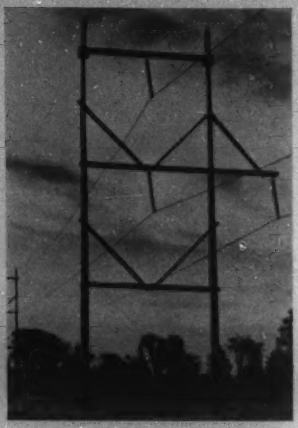

Figure 5. Type-*F* transposition structure

105-, and 110-foot pine poles. These structures were supported in all directions by means of sets of guys attached at the level of the horizontal braces and at points midway between these attachments and ground. Two spans away in each direction from the crossing spans, dead-end structures of normal height were installed, conductor heights having been graded down by the installation of poles of moderate lengths for the intermediate structures.

Guyed structures were installed as required by the rugged terrain and may be round at frequent intervals. Storm guyed and stabilizing structures as such were not used. The longitudinal strength of the assembled arm used in the type-*A* structure is such as to equal the unguyed strength of the supporting poles. The effect of one broken conductor is to deflect torsionally the whole structure, which deflection is resisted and limited by the remaining unbroken conductors and overhead ground wires. The overhead ground-wire bayonets bend under this condition, and the tops of the suspension insulator strings, moving, permit rotation of the crossarm in the horizontal plane. The conductor tension on the side of the structure opposite the break is relieved as well by the displacement of the insulator string, approximately eight feet in length, attached to the broken conductor.

Grounding

Overhead ground wires were connected to earth at all unguyed structures by means of pole ground wires and helical coils installed on each pole of the structures. Pole ground wires and helices were installed on every guy stub pole, and overhead ground wires were connected to earth through guy strands and these pole ground wires. Where stub poles were not required, the overhead ground wires were connected to earth by means of guy strands and anchor rods. Helical-coil grounds were installed on the butts of all poles, and, where pole ground wires were not installed, grounding conductors were extended from the butts of the poles to within a few inches below the ground line. Time did not permit the installation of an adequate grounding system during the construction period, though ground coils were installed for use as parts of that system, to be installed later. Wood strain insulators were installed in all conductor guys. The ungrounded ends of all these guys and all adjacent hardware were securely bonded to the insulator attachments to prevent possible charring of wood and radio interference.

Counterpoise

During the construction period and before the conductors and overhead ground wires were installed, resistances to earth of type-*A*-structure ground installations were measured. In this way a complete survey was made of ground resistances throughout the whole length of the line. A counterpoise system based upon this survey was designed and installed immediately following completion of the overhead construction.

In sections of the line where resistances were 30 ohms or less, no counterpoise conductors were installed. In sections where ground resistances were highest, approximately 750 ohms, four conductors were installed along the right of way and parallel to its center line. Counterpoise systems of three, two, and one conductor, according to measured resistances, were installed in other sections of the line. Solid galvanized-iron conductors of size 5 Birmingham gauge were buried by means of cable-laying plows to depths of 18 inches. Cross connections were installed to connect together all counterpoise conductors and all existing structure ground installations.

At all dead-end and guyed structures, all grounds, which included anchor rods and helical-coil grounds were connected together to form special low-resistance grids, which were, in turn, connected to the counterpoise conductors by means of cross connections. The entire overhead ground-wire system then had been connected to the counterpoise system by means of pole ground wires of the unguyed structures and the overhead ground-wire guys of the guyed structures.

Table I. Design Data

Type of construction	Single-circuit wood pole braced, *H*-frame with bayonet extensions
Operating voltage (design)	230 kv
Total miles of line	188
Right of way width	250 feet
Horizontal separation between center lines of circuits on same right of way	100 feet
Level ground span	520 feet
Average span	500 feet
Maximum span	1,300 feet
Poles (kind and class)	Southern yellow pine, western red cedar, and Douglas fir, Class 2
Treatment	Western red cedar, butts only; others, 8 pounds full pressure creosote
Normal pole length	60 feet
Conductor and pole separation	24 feet
Crossarms	Fir timbers, spliced, 50 feet over-all
Pole ground wires	Solid copper number 4 American wire gauge
Minimum ground clearance	32 feet
Minimum clearance to structure	86 inches, 76 inches to wood members
Loading class	National Electrical Safety Code, Fourth Edition—heavy
Conductors	Hollow design, 1.1 inches diameter, 500,000 circular mils
Overhead ground wires	Three number 5 copper-covered steel strand 30 per cent conductivity
Conductor tension (maximum)	9,000 pounds (41.5 per cent of ultimate strength)
Ground-wire tension (maximum)	4,300 pounds (36 per cent of ultimate strength)
Insulators	Spaced 5¾ inches, 15,000 pounds combined mechanical and electrical strength
Suspension insulator assemblies	Single strings, 15 units
Strain insulator assemblies	Double strings, 17 units
Counterpoise	One to four conductors as required
Counterpoise conductors	Solid galvanized iron 0.22-inch diameter
Line construction started	February 15, 1942
Line construction completed	July 3, 1942
Counterpoise installation completed	November 20, 1942

Total Insulation

The normal impulse flashover voltage (1½x40-microsecond negative wave) of conductors to ground of all suspension structures is 2,425 kv, which insulation is obtained by means of 15 suspension insulators spaced 5¾ inches and a wood strain insulator equipped with a flash gap of five feet, in series between conductor and ground. The impulse flashover voltage from conductors to pole ground wires through air is also 2,425 kv approximately. Under conditions of extreme conductor displacement and minimum clearance the impulse flashover voltage to ground of these structures is

1,500 kv. Impulse level of dead-end structures was raised to 2,620 kv by installation of two additional insulator units.

Ground-resistance measurements have not been made since the counterpoise installation was completed, though it is believed that the resistance to ground of any two adjacent span sections of the counterpoise system is not more than 30 ohms. Under conditions of minimum clearance of conductors to ground, currents of 50,000 amperes through the structure would be required to cause flashovers. Under normal conditions currents of 80,000 amperes would be required to produce flashover conditions. Less than one interruption per 100 miles of circuit per year is expected.

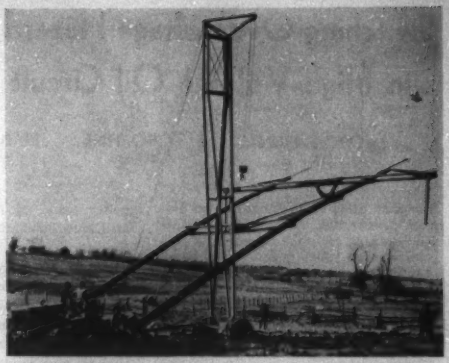

Figure 6. Special erection equipment

Conclusion

Circumstances which included an unfavorable season for outdoor construction and an extremely short construction schedule did not favor economical construction. Construction costs of these lines are not indicative of results that can be obtained under normal conditions. It is believed, however, that favorable costs can be obtained with wood construction for single-circuit 230-kv lines, though proof of this is not available at this time.

Time required for a thorough engineering study of the subject of 230-kv wood-pole line design was not available. The primary objective was to build a workable line within the shortest possible time and under circumstances which were adverse in many respects. Engineering studies, continued since construction work has been completed, suggest changes in details but indicate that the fundamental design is correct.

Wood construction for 230-kv transmission lines appears to be as practicable as for lower-voltage lines. Though steel may be available for construction of future 230-kv lines, it is believed that, in the interest of economy and improved operation, consideration should be given and further studies made regarding the use of wood supporting structures.

Switching Overvoltage Hazard Eliminated in High-Voltage Oil Circuit Breakers

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Synopsis: High-voltage transmission lines, when de-energized by conventional oil circuit breakers, are often subjected to high-voltage surges which present a real hazard to terminal equipment. The mechanism of surge generation is initiated by circuit-breaker restriking phenomena which are encouraged by the interruption of the large leading currents required to charge moderate and high-voltage lines. By interposing suitable resistors across the interrupting elements during the opening stroke of the breaker, the switching overvoltages may be either eliminated by preventing restriking or so reduced in magnitude in the event of restriking that the system is relieved of their hazard. The development of this achievement is presented chronologically:

1. Theoretical considerations
2. Transient-analyzer studies
3. Power-laboratory switching tests
4. Actual field tests on the 220-kv lines of Southern California Edison Company Ltd. at Boulder power plant

IT has been recognized for many years that some of the most severe switching surges encountered in the field are those which attend the interruption of line charging current. Tests on miniature systems have indicated that transient voltages of the order of six or seven times normal line-to-neutral crest may be obtained during such switching,[1-3] Field data, in general, substantiate such predictions.

In this paper a specific problem of high transient switching voltages on the 220-kv lines of the Southern California Edison Company Ltd. is discussed. The particular line which was being subjected to these overvoltages was initially operated as a single line with three ground-fault neutralizer coils located at Boulder power plant, at Barre substation, and at Chino substation.[4] At the present time another line is in service, and both lines are normally bussed at Boulder power plant and operated as part of the extensive 220-kv solidly grounded system. After diagnosing the symptoms from a theoretical standpoint, a complete analysis was made, using the transient analyzer to determine the possible magnitudes of switching overvoltages under various possible system-operating conditions. Various means of subduing these overvoltages were carefully considered, drawing on experience in related fields, and it was concluded that equipping the circuit breakers with internal resistors of the proper ohmic value afforded the best solution.

The paper presents the story of this development starting from theoretical considerations. Some results of analytical studies are presented as well as power-laboratory test results. A large portion of the paper is devoted to the field testing at Boulder power plant and interpreting the results obtained.

The effectiveness of the method described in controlling the switching overvoltage hazard is significant, not only from the circuit breaker standpoint, but from the arrester, relaying, and over-all system-operating standpoint as well, since lines and terminal equipment are freed from the possibility of being subjected to destructive switching overvoltages, regardless of the method of system neutral grounding.

Conclusions

1. Transient overvoltages due to switching can be reduced to harmless values by equipping the circuit-breaker interrupters with internal resistors of the proper ohmic value (see Figure 11).

2. While it has been previously recommended that the ground-fault neutralizer be short-circuited during switching operations at these high operating voltages, these tests show conclusively that this short-circuiting operation is not necessary when the breaker is equipped with such resistors.

3. From the standpoint of the magnitude of switching overvoltages, it makes no practical difference whether the system is in tune with the neutral reactance or not when switching is done by means of breakers equipped with such resistors.

4. Holding the transient switching voltages to moderate levels reduces the arrester duty to that of discharging lightning surges alone, thus minimizing arrester operations.

5. When interrupting fault currents, oil circuit breakers equipped with such resistors experience reduced power arcing as a result of the reduced rate of rise of recovery voltage (see Figure 8).

6. The major results of the tests at Boulder power plant confirm earlier conclusions reached through theoretical approach followed by a complete transient-analyzer study and power-laboratory tests.

Theoretical Considerations

Since the phenomena of the interruption of leading (capacitive) currents at power-system voltages are encountered when de-energizing (1) transmission lines, (2) cables, and (3) capacitor banks[5] (see Figure 1), it should prove profitable to review the fundamental nature of the phenomena in order to grasp a working knowledge of the problems. In so doing, it will be compared in its essential differences with the interruption of lagging (inductive) currents of the short circuit. Terms and concepts will be revealed in this section. The study of this section however is not imperative to the knowledge of the results of the paper.

From the outset, a group of extremely contrasting relations arise. First the lagging current of the short circuit deals primarily with heavy currents which approximate the full interrupting rating of the breaker. All leading currents, however, are relatively small, and, consequently, the light current characteristics of the breaker are involved. In the tank-type oil breakers these differences are largely hydraulic, the interrupters being designed to do their most effective work at heavy currents. Hence the interruption of any leading currents by the tank-type breakers does not profit by the insulating characteristic provided by the most effective oil-blast action. Circuit differences are so great, however, that the above features become of secondary importance.

The Inductive Interruption

A representative interruption of the inductive current is shown in Figure 2. Here, following contact separation, attempts at interruption occur at the first two current zeros. Each time the arc was *rekindled* by the rapid rise of recovery voltage across the breaker, approaching twice normal crest in a matter of microseconds. With the rekindling of

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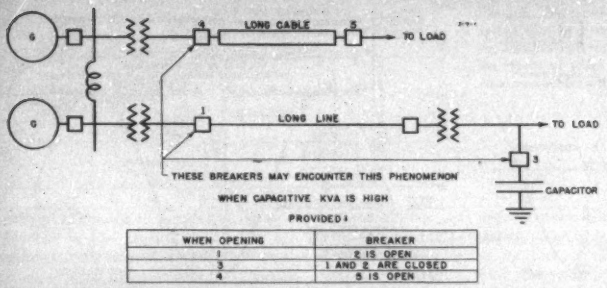


WHEN OPENING	BREAKER
1	2 IS OPEN
3	1 AND 2 ARE CLOSED
4	5 IS OPEN

Figure 1. Principal circuit conditions which may give rise to overvoltages of the type described in this paper

the arc, the accumulated circuit effects are completely liquidated at each current zero, and the current continues anew, as if nothing had happened, to repeat the attempt at the next current zero under more favorable conditions of contact parting and gap insulation. The characteristic of liquidating all accumulated debts at each current zero is a desirable property of the inductive circuit.

The Capacitive Interruption[2,3]

When the first current zero in the arc arrives in the passage of a leading current, interruption occurs quite easily. This comes about since the capacitive load retains the instantaneous voltage of the source at the instant of current zero, and for several hundred microseconds following there is little or no voltage across the breaker. The breaker thus mirrors an overconfident attitude in its ability to interrupt the circuit with the extremely small contact separation associated with the first current zero in the arc. All debts have not been liquidated, however, as one-half cycle later (see Figure 3) the bus voltage has reversed, and approximately double voltage thus appears across the breaker. If the breaker passes this peak without *restriking*, as does happen at limited kilovolt-amperes (short lines), then the confidence is justified, and no disturbance occurs. At higher kilovolt-amperes, however, when the arc develops more disturbance, the short arc gap cannot withstand the double voltage, and restriking occurs. At the time of restriking, the capacitor finds itself in the embarrassing position of being charged opposite to the desires of the bus voltage. In its eagerness to adjust the situation, a flow of current occurs which must be limited by the inductance of the circuit and, in good oscillatory style, permits the voltage to overshoot its mark by the initial difference. In this manner the voltage reaches minus $3E$ at the exact instant that the transient current passes through zero.

From this point two possibilities of major interest arise (Figure 3), namely:

(*a*). Interruption of the high-frequency current at the first current zero (case 1).

(*b*). Continuation of the high-frequency current, permitting it to die away, resulting in the re-establishment of the normal frequency capacitor current (case 2).

If the latter occurs, then interruption will again take place at the next current zero of the normal frequency current which is just one cycle after the first current zero in the arc. By this time the gap insulation will have increased, and subsequent restriking is usually avoided; hence final interruption is achieved. In this case the voltage to ground may rise to only three times normal crest on a single-phase basis. If on the other hand, the breaker permits the interruption of the high-frequency current at the first current zero following restrike, then the capacitor or line remains charged to as high as three times normal voltage crest. Then one-half cycle later, when the bus voltage again reverses, it permits a maximum of four times normal voltage to appear across the gap insulation. Subsequent restriking usually can be expected under these very severe conditions. In this manner voltages up to insulation breakdown values can be generated. The reduction of these overvoltages is the subject of this paper.

The above rough analysis of the interruption of the capacitive circuit, although more descriptive for the capacitor, applies equally well for the distributed case of the long open-circuited high-voltage line or cable. Here the voltage oscillations are more square-topped because of the traveling wave property of the load. As the line, for example, remains charged at the crest value of the voltage with the early interruption of charging current, double voltage then appears across the breaker with the reversal of the source voltage. If restriking occurs at the peak of this reversal, a voltage wave equal to the difference, or twice normal voltage crest, travels down the line to establish a charge equal and opposite to the initial trapped charge. The breaker current associated with this restrike is equal to the voltage of the traveling wave divided by the surge impedance of the line, about 500 ohms. When these waves reach the far end of the open line, the voltage wave reflects without change of sign to sweep back to the breaker, establishing a charge of approximately three times normal voltage crest. The accompanying current wave, however, reflects with change of sign to cancel the forward wave current. Hence current zero literally travels back to the breaker. When it arrives, the breaker arc is usually extinguished, thus leaving the line charged close to three times normal voltage crest. On a 200-mile line the complete round trip of such a wave from restrike to current zero at the breaker requires about 2,000 microseconds or about an eighth of a sixty-cycle wave. On a 10-mile cable the round trip requires about 200 microseconds.

Resistors

When resistors of the proper ohmic value are placed across the interrupting elements in the breaker, they function to reduce the probability of restriking by allowing the voltage on the load side to follow more closely the voltage of the source (see Figure 4). The resistors not only reduce the net voltage across the breaker but also act to distribute this voltage more equally within the breaker, thus lowering the maximum voltage per break which in turn further reduces the probability of restriking. It follows that should restriking occur (see Figure 4, case II), the net voltage difference (which defines the amplitude of the voltage oscillation about the generated voltage) is reduced, and hence the peak voltage to ground is lowered accordingly. To this reduction should be added the additional lowering of the peak voltage afforded by the damping attributable to the resistor. The combination of these several effects

1. Makes possible a higher capacitance kilovolt-amperes that may be switched with a given breaker without restriking.

2. Reduces the hazards of restriking in the kilovolt-amperes region where restriking is more probable.

The first of these advantages is the primary objective of the addition of resistors

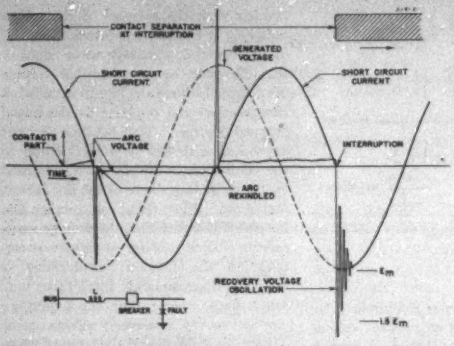


Figure 2. Typical interruption of an inductive short circuit showing arc rekindling at early current zeros

Compare with the interruption of the capacitive circuit shown in Figure 3

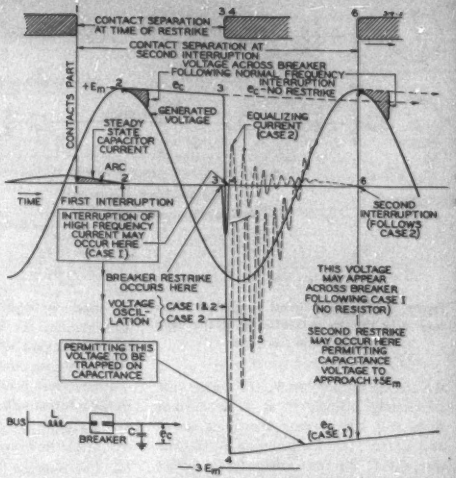


Figure 3. Capacitive circuit interruption which shows a breaker-restriking phenomenon together with two possibilities of eventual interruption

This figure with the modification shown in Figure 4 is the theme of this paper

to breakers required to interrupt heavy capacitive kilovolt-amperes.

The resistor current is interrupted within the breaker as a plain-break interruption, care being taken that the resistor is so proportioned that the voltage surge associated with this final interruption does not exceed twice normal leg voltage crest. The design and arrangement of the resistor will be discussed later in the paper.

Transient-Analyzer Results

In order to make a thorough analysis of the effectiveness of shunt resistors in reducing the magnitude of switching surges, the transient analyzer[4] was used. The system studied in connection with this specific problem is shown in Figure 5. This miniature system is an approximate reproduction of the actual system at Boulder power plant on which the final field-test data were obtained.

By means of a synchronous switch which has been previously described,[4] each phase could be switched in sequence, or restrikes could be imposed in any one phase during the clearing process.

Oscillograms of such restriking are shown in Figure 6a for the first phase to clear with the system neutral solidly grounded. Voltages across the switch contacts are shown to reach values between four and five times normal line-to-neutral crest with two restrikes without resistors. When resistors are used (4,600 ohms in this case), these voltages are substantially reduced, as shown by other oscillograms in the same figure.

Line voltages to ground are also shown in Figure 6b. It is evident from these oscillograms that the shunt resistors are effective in

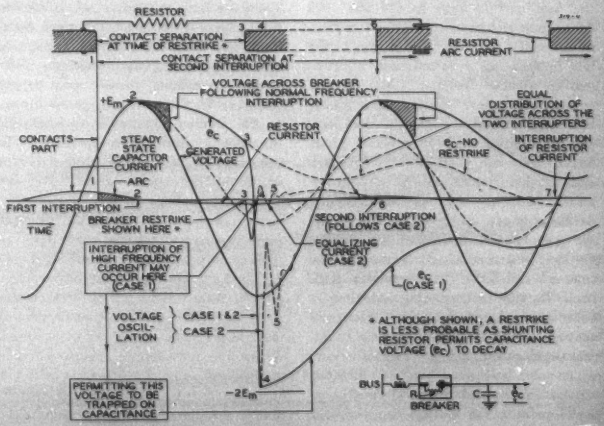
1. Reducing the a-c voltage on a line being switched out before the final break is completed.
2. Reducing the d-c voltage left on a line.

Bus voltages to ground are shown in Figure 6c. With no restriking, the bus voltage at the source is seen to drop noticeably because of the interruption of leading current. However, if restriking takes place, rapid changes in bus voltage can occur which may reach relatively high magnitudes as shown. Voltages on the bus side may be considerably higher than these if the neutral impedance is high.

A representative indication of the severity of overvoltages is the voltage across the breaker contacts during interruption. Therefore, the generalized

Figure 4. Typical capacitive circuit interruption when resistors of proper ohmic value are inserted in the circuit during the interrupting period

Compare with Figure 3



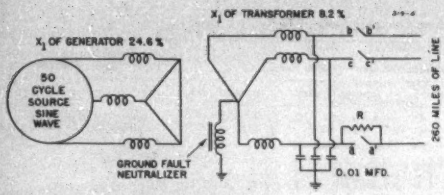


Figure 5. Miniature system studied with the transient analyzer the results of which are shown in Figure 6

curves of Figure 7 show this voltage as a function of the amount of shunting resistance R for various system conditions. It appears from these curves that there is no particularly critical value of shunt resistance required, but that any value of the order of 2,000 to 4,000 ohms would accomplish a very substantial reduction in overvoltage severity, regardless of the method of system grounding and for any phase to clear, that is, whether it is the first, second, or last phase to clear.

It can be shown that the effectiveness of a shunt resistor used in this manner depends upon the length of line. If a resistor is selected on the basis of sufficiently reducing transient overvoltages for the longest line that a given breaker is likely to be called upon to interrupt, then that resistor should be even more effective in reducing transient switching voltages for shorter lines, although the surge associated with the interruption of resistor current is likely to be slightly increased.

Laboratory Tests

The transient-analyzer solutions covering a wide range of probable circuit and breaker characteristics made another valuable contribution to the study by indicating

1. Critical circuit constants to be investigated.
2. The value of resistors which should prove most helpful in reducing overvoltages.

This information reduced the number of laboratory tests necessary, but even so over 400 tests were made in the power laboratory at Schenectady. However, the analyzer cannot indicate the restriking characteristics of the breaker, and hence power tests are essential. A study of the analyzer data indicated that, under the adopted assumptions with respect to breaker performance, a resistance between 2,000 and 4,000 ohms would be successful in holding the overvoltages, because of restriking, between 1.9 and 3.2 times normal over a practical range of circuit constants (including presence of ground-fault neutralizer).

Resistor designs were made up covering this range with the thermal requirements both on closing and opening under the worst field conditions in mind. The most satisfactory compromise, considering all factors, indicated a total resistance of 3,000 ohms per phase. Each resistor consists of a helically wound resistance wire which in turn is helically wound on a Herkolite tube. This winding is protected by an outer tube as shown in Figure 9. One resistor is connected in parallel with each interrupter as shown schematically in Figure 10. As the breaker opens, the power arc is interrupted in the interrupting elements, thus throwing the resistors (1,500 ohms apiece) in series with the line. As the crosshead (Figure 10) leaves the interrupting elements, the small unity power-factor resistor current is drawn as an arc between the external contacts and interrupted under plain-break conditions with a minimum of disturbance. The resistor also enters the circuit first when closing the breaker.

Leading current tests in the power laboratory were made by switching various banks of capacitors with a 230-kv oil circuit breaker, equipped with resistors as described above. Numerous tests were made also without resistors, although they were limited because of frequent arrester operations. Although the capacitor banks do not afford the traveling-wave phenomena associated with the long line, the switching problem is similar in all major respects. Therefore, the information obtained is applicable directly to the long line problem. The laboratory tests without resistors in the breaker did not reveal the true maximum voltages as protective arrester operations were encountered in many cases. The results of these tests demonstrated the ability of such resistors to hold switching overvoltages to very safe levels. This was particularly noticeable by the absence of arrester operations during tests in which the resistors were employed. Following the leading kilovolt-ampere tests the breaker, equipped with resistors, was tested on short-circuit interrupting duty

1. To test the mechanical features of the resistor element.
2. To observe the effect of the lower recovery rate; contributed by the resistor, on the arc duration.

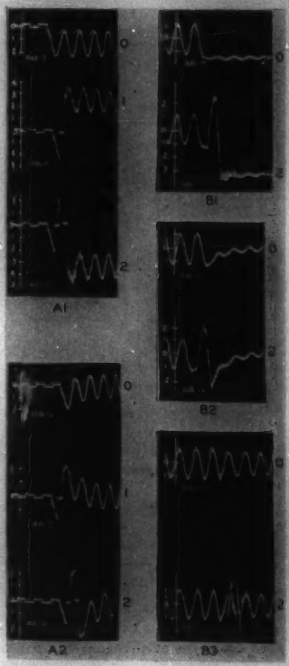


Figure 6. Transient-analyzer oscillograms illustrating the phenomenon of line-charging current interruption with and without shunting resistor in the miniature system of Figure 5

The ordinate is times normal line-to-neutral crest voltage

Numbers on oscillograms show number of restrikes in each instance

A. Voltage across the switch in phase *a*
A1. No shunting resistor
A2. 4,600 ohms shunting resistor
B. Line-to-ground voltage on line side of switch in phase *a*
B1. No shunting resistor
B2. 4,600 ohms shunting resistor
C. Line-to-ground voltage on source side of switch in phase *a*. No shunting resistor

Figure 8 shows the observed reduction in arcing time afforded by the reduced recovery rate. Breaker disturbance, contact burning, and oil carbonization are also reduced. The success of these tests led to the desirability of field confirmation on the Boulder circuits.

Field Tests

Such a series of field tests was made during the weekend of March 27 to 30,

Table I. Boulder Power-Plant Line-Dropping Tests—230 Kv

Test No.	Miles Line	Resistors	Neutral Reactor	Circuit Connection	Maximum Voltages*—Times Normal Crest: Bus-to-Ground A	B	C	Line-to-Ground A	B	C	Across Breaker A	B	C	Crosshead Travel in Inches From Contact Separation to Interruption of Last Phase: Inside Interrupters	Final Break (Stroke = 36 Inches)
1A					1.6	1.1	1.1	2.0	1.0	1.4	3.0	1.5	2.6		2¾
1B				2 generators	1.1	1.1	1.2	1.3	1.3	1.3	2.2	2.0	2.2		2½
1C	132	Out	Short-circuited	2d line	1.0	1.0	1.0	1.0	1.0	1.2	2.0	2.0	2.1		1
1D					1.8	1.1	1.1	2.0	1.4	1.1	2.4	2.4	2.0		1⅝
1E					1.1	1.1	1.1	1.6	1.6	1.4	2.7	2.0	2.6		2½
2A					1.1	1.1	1.0	1.6	1.3	1.6	2.4	2.2	2.3		2⅜
2B				2 generators	1.1	1.1	1.1	1.3	1.2	1.7	2.2	2.4	2.5		2⅜
2C	233	Out	Short-circuited	2d line	1.3	1.1	1.6	1.2	1.4	1.9	1.8	2.4	3.0		2¾
2D					1.6	1.2	1.5	2.2	1.2	1.8	3.0	2.0	3.0		3½
2E					1.1	1.2	1.2	1.4	1.7	1.7	2.4	2.4	2.2		2½
3A					1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1½	10½
3B				2 generators	1.0	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1	9½
3C	132	In	Short-circuited	2d line	1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1½	9
3D					1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1	9½
3E					1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1	11½
4A					1.3	1.0	1.1	1.5	1.1	1.2	1.5	1.4	1.0	1½	9½
4B				2 generators	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1½	9½
4C	233	In	Short-circuited	2d line	1.1	1.1	1.6	1.3	1.1	1.6	1.4	1.1	1.5	1½	10½
4D					1.0	1.1	1.1	1.1	1.0	1.0	1.1	1.4	1.0	½	9½
4E					1.0	1.1	1.1	1.0	1.1	1.0	1.5	1.3	1.1	1	8½
5A					1.6	1.6*	2.0*	1.5	1.2	1.0	1.4	1.2	1.0	1½	14
5B					1.7*	1.4*	1.5*	1.0	1.3	1.1	1.0	1.0	1.0	1½	11½
5C	132	In	Tap 7	1 generator	1.7	1.7	1.7*	1.7	1.0	1.0	1.6	1.1	1.1	2½	13½
5D					1.6*	2.0*	1.5*	1.2	1.0	1.2	1.1	1.0	1.0	1½	14½
5E					1.9*	1.5	1.5*	1.7	1.1	1.0	1.6	1.2	1.0	2½	14
6A					1.6	1.6*	1.5	1.5	1.5	1.2	1.8	1.6	1.3	2½	12¾
6B					1.5	1.5	1.4*	1.2	1.5	1.3	1.3	1.5	1.2	2½	12¾
6C	233	In	Tap 7	1 generator	1.4	1.7	1.4	1.3	1.4	1.3	1.2	1.5	1.2	2½	11¾
6D					2.0	2.0*	1.4*	1.6	1.0	1.0	1.5	1.4	1.0	2½	12¾
6E					1.4*	2.0	1.6	1.1	1.7	1.0	1.3	1.6	1.2	2½	10½
6F	233	In	Tap 3	1 generator	1.1	1.6	1.4*	1.2	1.4	1.3	1.5	1.4	1.3	2½	11½
6G					1.2*	1.6	1.7	1.1	1.6	1.5	1.4	1.5	1.4	2½	11½
7-1-A					1.1	1.1	2.0	1.1	1.1	1.7	1.1	1.9	2.7	2½	
7-1-B					1.1	2.0	1.9	1.1	2.0	1.9	1.5	2.6	2.4	3½	
7-1-C	132	Out	Short-circuited	1 generator	1.2	1.3	2.1	1.2	1.5	1.7	2.0	2.3	2.6	3½	
7-1-D					1.2	1.4	1.5	1.1	1.2	1.1	1.5	2.1	1.8	3	
7-1-E					1.3	1.2	1.2	1.3	1.1	1.3	1.6	1.9	2.3	2½	
7-2-A			Tap 9**		2.4	2.2	2.2	1.8	2.0	2.7*	2.1	2.9	3.2*	4½	
7-2-B	132	Out	Tap 10**	1 generator	3.6	2.8	2.7	2.4*	1.6	1.6*	3.5*	3.2	4.3*	5	
7-2-C			(Tuned system)		2.6	2.3	2.2	1.6	1.6	2.1*	2.2	3.1	2.4*	4½	
7A	132	Out	Tap 7	1 generator	2.9	4.4*	3.2	2.1	4.4*	3.2*	3.3		4.6*	6	

* Maximum voltages to ground recorded for both the bus and the line side of the breaker include voltages encountered either in the course of the primary interruption within the interrupters or in the course of the interruption of resistor current by the external break (see Figure 10). Voltages encountered in the interruption of resistor current are marked by an asterisk. For maximum voltage across the breaker only voltages occurring in the course of the primary interruption are recorded, since voltages across the breaker during the interruption of resistor current involve no stress on solid insulating material other than that occasioned by voltages to ground on either side of the breaker. Voltage across the breaker during the interruption of resistor current never exceeded twice normal line-to-neutral crest.

* Reading affected by flashover in voltage divider. Approximate correction applied.

** Two reactors were connected in parallel; one on tap 9 and one on tap 10.

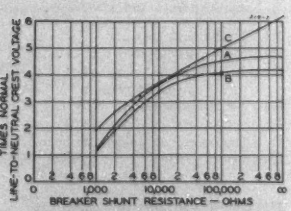


Figure 7. Effect of breaker resistors in reducing transient overvoltages during switching

Voltages shown are the maximum possible across the breaker for two restrikes in the phase being switched for any phase to clear, that is, first, second, or last

A—System neutral solidly grounded

B—System neutral grounded through ground-fault neutralizer tuned to 260 miles of line

C—System neutral grounded through ground-fault neutralizer tuned to half (130 miles) of the total of 260 miles being switched

1942, on the 230-kv number 8 oil circuit breaker in the switchyard of the Southern California Edison Company at Boulder power plant. This breaker is a tank-type breaker which contains multibreak interrupters[7] and has an interrupting rating of 2,500,000 kva and an interrupting time rating of five cycles. The voltage-limiting resistors, previously described, are mounted on the interrupters as shown in Figures 9 and 10.

All tests were circuit opening in which only the charging current of the connected line (far end open) was interrupted—commonly termed line-dropping tests. In this type of interruption, leading currents involved are small. Thus, within reasonable limits, arcing time is no important consideration. On the other hand, unless precautions are taken, breaker restriking quickly generates overvoltages which may be

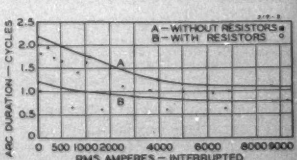


Figure 8. Breaker arcing time during the interruption of inductive short circuits, showing the improvement as a result of reduced recovery rates and better internal voltage distribution brought about by resistors in the breaker

harmful to the breaker itself and to other connected equipment. Control of these overvoltages was therefore the primary concern in these tests, and the purpose of the test program was to determine

1. The nature and magnitude of the overvoltages under various system conditions.

Figure 9 (left). General Electric multibreak interrupter unit for 230-kv oil circuit breaker with resistor attached

Two such interrupters are used per pole as shown in Figure 10

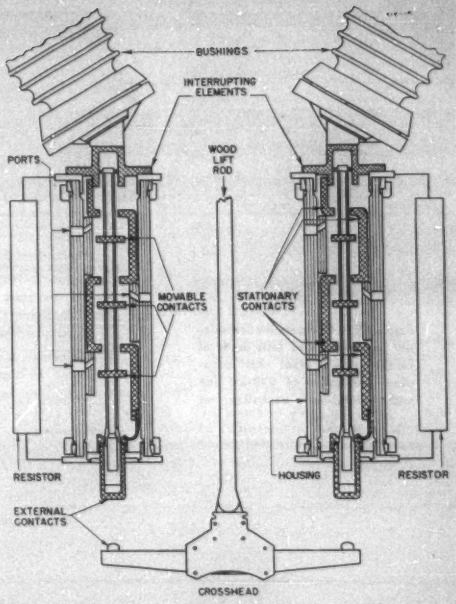


Figure 10 (right). Schematic diagram showing the multibreak interrupters with resistors attached

The resistor current is interrupted in the gap formed by the external contacts

2. The effectiveness of resistors assembled in the breaker, in parallel with the interrupters, in reducing these overvoltages to harmless values.

This approach naturally required that the line-dropping test program should include various practical system conditions with and without resistors in parallel with the interrupters. The following conditions were subjected to change:

1. The length of line being disconnected.
2. The neutral connection.
3. The nature of the power source.

Circuit Conditions

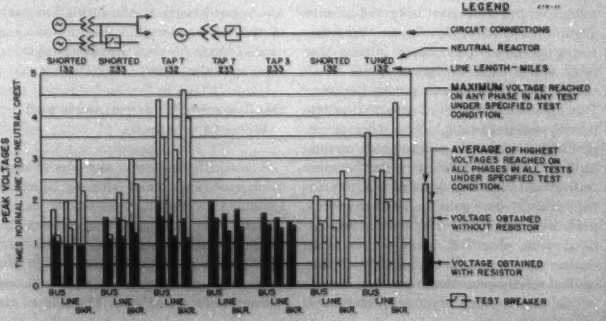
1. In some tests the entire 233-mile line to Chino substation was disconnected at Boulder power plant; in others only the 132-mile section to Pisgah substation.

2. In some tests the neutral was solidly grounded; in others it was grounded through reactance were used; one of these values was that required for tuning as a ground-fault neutralizer to the line length being disconnected; the other two values, corresponding to other neutralizer tap settings, have been used to tune the line in conjunction with additional reactors at the far end of the line and consequently correspond to reactances above the tuned value.

3. In some cases two local generator-transformer units were connected to the bus, and the remainder of the system was tied in through the second line to Chino substation. In the others only one generator-transformer unit was connected to the bus, and there was no tie with the rest of the system.

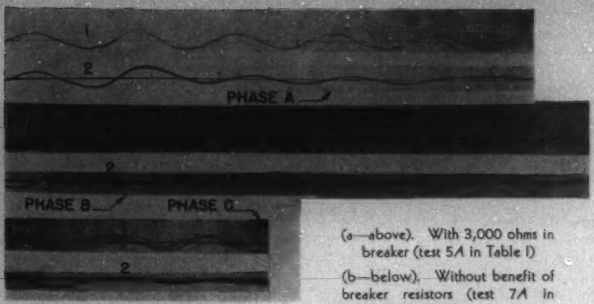
Figure 11. Pictorial summary of results of oil-circuit-breaker tests made at Boulder power plant March 28 and 29, 1942

Comparison of voltages caused by interruption of transmission-line charging current. Here the overvoltages obtained with and without breaker resistors, under various line and ground conditions are shown



Test Results

A total of ten groups of tests was made at Boulder power plant covering practical combinations of circuit and breaker arrangement. Table I describes the results of these tests with respect to the maximum voltages developed and with respect to the breaker crosshead travel necessary for interruption. The overvoltage record, with and without resistors, is presented graphically in Figure 11 in such a way that the effect of the resistors, of the

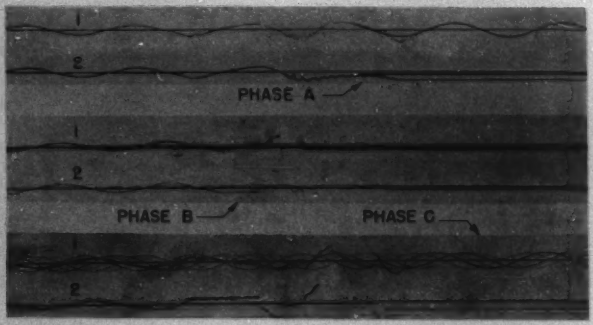


(a—above). With 3,000 ohms in breaker (test 5A in Table I)

(b—below). Without benefit of breaker resistors (test 7A in Table I). During this test a 220-kv bushing flashed over

1. Voltage to ground on bus side of breaker
2. Voltage to ground on line side of breaker

Figure 12. Comparative cathode-ray oscillograms of tests made at Boulder power plant when dropping 132 miles of 230-kv line with ground-fault neutralizer on tap 7



length of line, and of the ground-fault-neutralizer tap setting are readily apparent.

In the course of these field tests, three arrester operations were observed, one on phase *a* and two on phase *c*. These arresters are located near the terminals of the 82,500-kva transformer bank at Boulder power plant which is about one mile from the Southern California Edison Company switchyard. These three arrester operations all occurred during the tests which used the ground-fault neutralizer and no resistors in the breaker. During an earlier series of tests at Boulder power plant, at which time the above problems were being diagnosed, under similar system conditions (with the neutralizer untuned and without resistors in the breaker) six lightning-arrester operations were observed. No arrester operations were observed, however, for ten similar tests made at that time with the neutral solidly grounded.

The interrupters were completely examined at four points in the test program. There was no damage to the contact or insulation parts as a result of any of the tests made when the resistors were connected. On the last inspection following tests with the ground-fault neutralizer and without resistors (during one of which tests with the neutralizer untuned the breaker flashed over externally), there was some damage to the insulation parts of the interrupters but not of sufficient magnitude to prevent the successful interruption of the circuit.

Oscillograph Measurements and Records

A good illustration of the effectiveness of internal resistors in reducing transient switching overvoltages is shown in the cathode-ray oscillograms of Figure 12, which places together for easy comparison a test with a 3,000-ohm resistor in the breaker (Figure 12a) and a duplicate test without resistors (12b). These tests are numbers 5A and 7A respectively (Table I), in which 132 miles of line were dropped with the ground-fault neutralizer on tap 7. Figure 12a shows no overvoltages of any consequence although there is restriking during the clearing period. In contrast the restriking associated with Figure 12b (no resistors) results in violent transient disturbances which were so high as to cause sparkover of a protective gap in the cathode-ray-oscillograph measuring circuit which made it impossible to determine accurately the actual crest voltage obtained. The voltages reached for this test, however, were high enough to sparkover the 220-kv bushing on the source side of the breaker. This would require a maximum of 1,050-kv crest, depending upon several factors, the most important of which are the wave shape of the transient voltage and the lower humidity, both of which would lower the actual flashover.

The oscillograms of Figures 13a and 13b are the magnetic oscillograph records of the same field tests as presented in Figure 12, namely tests 5A and 7A respectively of Table I. In Figure 13a the duration of the unity-power-factor resistor current is clearly shown. Characteristic restrike current surges are shown in Figure 13b. Here four separate restrikes took place, all of which interrupted with the arrival of the first current zero of the high-frequency oscillation. Figure 13 also exhibits oscillograph measurements of phase current, trip coil current, and breaker travel.

Voltage to ground on each side of each pole of the test breaker was indicated on the cathode-ray oscillograph. The deflection plates of this oscillograph were energized by means of capacitance potentiometers, the upper section of which was furnished by the carrier-current coupling capacitors on the two transmission lines. This provided an arrangement capable of reproducing satisfactorily voltages of all types from the high-speed transients obtained upon a restrike in the circuit breaker to the slowly leaking charge left on the lines upon final interruption.[9] The two voltages for each pole of the breaker were recorded on parallel traces on the same film, so that the voltage across the breaker pole could be determined readily by graphical subtraction.

Discussion of Results

Figure 11 shows the effect of the resistors upon the overvoltages attending switching. As is indicated by this figure three pairs of test groups were taken in such a manner that direct comparison can

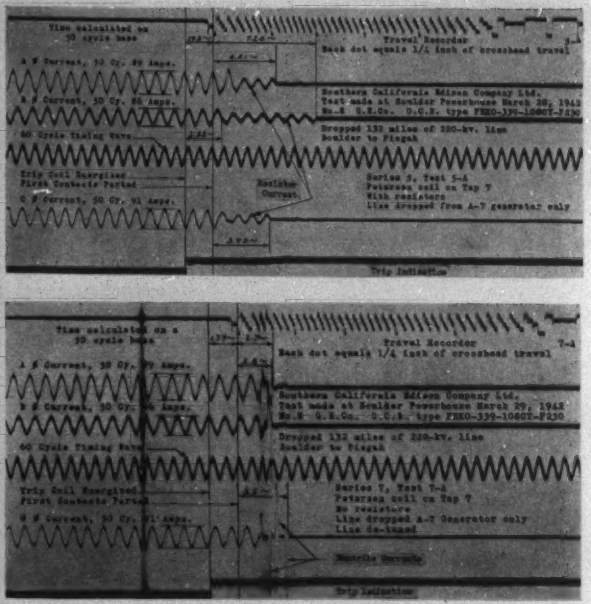

Time calculated on
50 cycle base
Travel Recorder
Each dot equals 1/4 inch of crosshead travel
A ϕ Current, 50 Cy. 89 Amps.
B ϕ Current, 50 Cy. 86 Amps.
Southern California Edison Company Ltd.
Test made at Boulder Powerhouse March 29, 1943
Oscillograph Co. type FEKO-339-106CT-F230
60 Cycle Timing Wave
Dropped 132 miles of 220-kv. line
Boulder to Pisgah
Trip Coil Energized
First Contacts Parted
Neutral Current
Series 7, Test 7-4
Peterson coil on Tap 7
With resistors
Line dropped from A-7 generator only
C ϕ Current, 50 Cy. 91 Amps.
Trip Indication

Figure 13. Magnetic oscillograms associated with the voltage records of Figure 12

(a—top). With breaker resistors. Note resistor current

(b—bottom). Without resistors. Four separate restrikes occurred on this test of the type shown in Figure 3, case I

be made to show the effect of the resistors. In these cases, and also in the other groups taken with the resistors connected, the voltage was limited to twice normal line-to-ground peak or less—both when the resistor was being switched in and when the resistor current was being interrupted. When the resistors were not connected, on the other hand, the voltage across the breaker reached three times normal with the neutral solidly grounded and more than four times normal with a neutral reactor connected.

Correspondingly, as shown in Table I, the resistors bring about a considerable reduction of arc length inside the interrupters as a result of the improved internal voltage distribution and the improvement in the rate of rise of recovery voltage. The residual current which remains in the resistors is then interrupted by the disconnecting break (formed by the crosshead, Figure 10) in from about 15 per cent to approximately 35 per cent of their available break distance. Here also the resistors are effective in preventing any build-up of voltage beyond the values shown in Table I and Figure 11.

The fact that the resistors produce such a substantial reduction in overvoltage makes them preferable to other measures, since they afford protection thereby to other terminal apparatus. Unless the breaker is sufficiently positive in action to prevent restriking and its associated overvoltages, therefore, the use of resistors appears desirable whenever the length and voltage of the lines are such as to give rise to trouble of this type. Because of the dependence of this restriking phenomena upon so many factors, the most important of which is the breaker characteristic, it is impossible to indicate here the capacitance kilovolt-amperes where restriking can be expected to occur. Tests at 15 kv on one manufacturer's breakers,[5] for example, indicated a limit of 10,000 capacitive kilovolt-amperes above which overvoltages could be expected without the aid of internal resistors. The 132 miles of line dropped, as exhibited in Figures 12 and 13, represents about 35,000 capacitive kilovolt-amperes. These values cannot be compared directly with those shown at 15 kv, however, because of the wide difference in voltage levels. The above makes clear that when small capacitive kilovolt-amperes are to be interrupted, with standard power breakers (short lines or cables, protective capacitors, and so forth), no trouble should be expected.

The operations in all the tests presented in this paper were confined to dropping a length of open transmission line, but, since breaker operation upon all except three-phase faults involves dropping at least one unfaulted phase conductor, the phenomena will be present in practically all breaker operations.

The results of these tests are in good qualitative agreement with the results of miniature-system tests as regards the principal features:

1. With the untuned neutral reactor, voltages obtained without the resistor were much higher than those obtained with the neutral solidly grounded.

2. The resistors brought about a substantial reduction of voltage in all cases, and, the higher the initial overvoltages, the greater was the percentage reduction.

A comparison of the overvoltages obtained for the tuned ground-fault neutralizer with those obtained for the solidly grounded system indicates the desirability of supplementing miniature test with full-scale tests under actual conditions. This is emphasized by the fact that the voltages associated with test series 7–2 are very high, relative to those obtained for test series 1, which was the solidly grounded case with the same line length. From earlier studies, on the other hand, it had been concluded on the basis of the transient-analyzer results that interrupting line charging current in a ground-fault-neutralizer system is no more difficult from a switching standpoint than in the same system with neutral solidly grounded. The reason for this disagreement apparently lies in the fact that surges communicated to one phase by clearing or restriking in another were of much more importance in the ground-fault-neutralizer tests than with the neutral solidly grounded. Not only did this have a direct bearing on voltage magnitudes, but in a number of cases it appeared to be directly responsible for additional restrikes which contributed still more to the overvoltages. In the grounded neutral tests there was never more than one restrike which contributed appreciably to the building up of voltage, but several times there were two in the ground-fault-neutralizer tests. Since the miniature-system tests were based on the assumption of two restrikes with the worst timing, the full-scale grounded-neutral tests produced overvoltages considerably lower than predicted. The ground-fault-neutralizer overvoltages

were about equal to predicted values, the loss caused by the fact that the worst timing was not realized being approximately balanced by the increase arising from interphase reaction.

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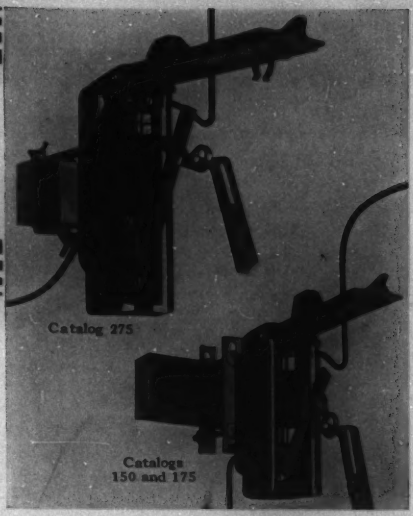

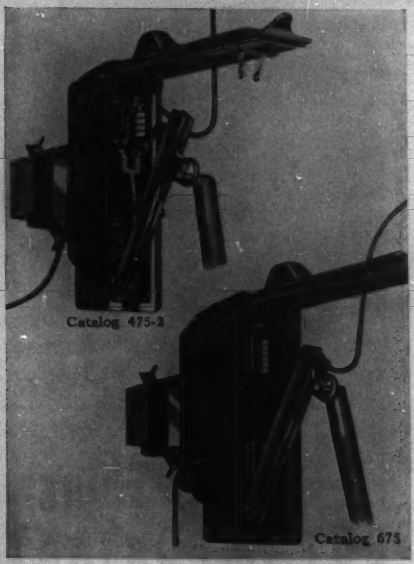

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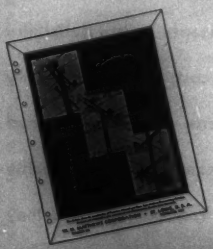

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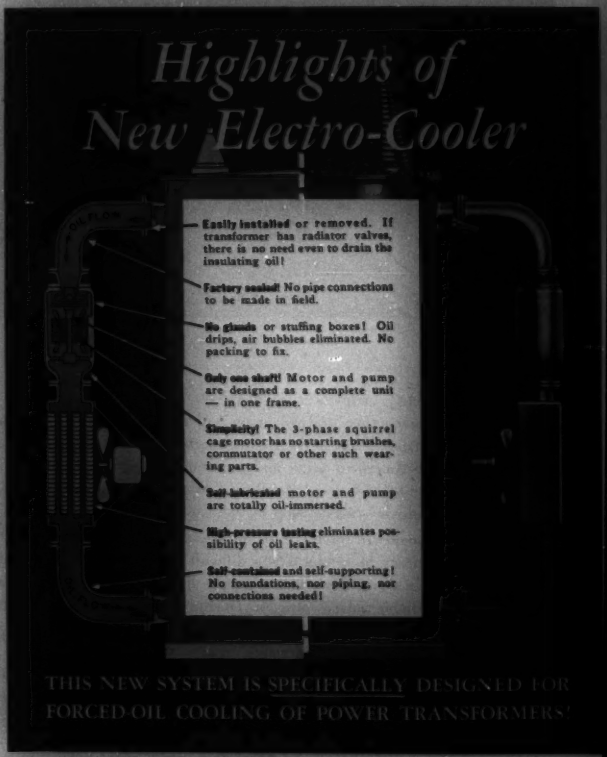
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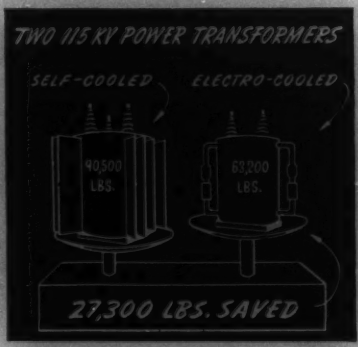
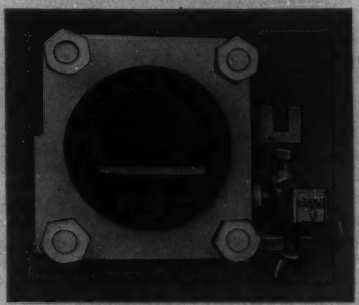


Savings like these in copper and steel — an average of 25% — can be made on every contemplated power transformer installation.



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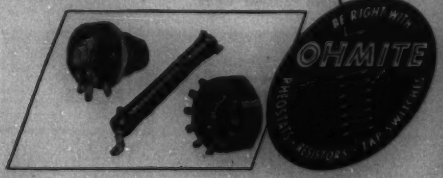

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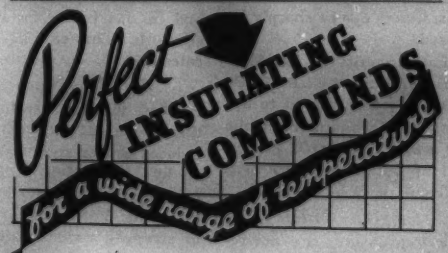

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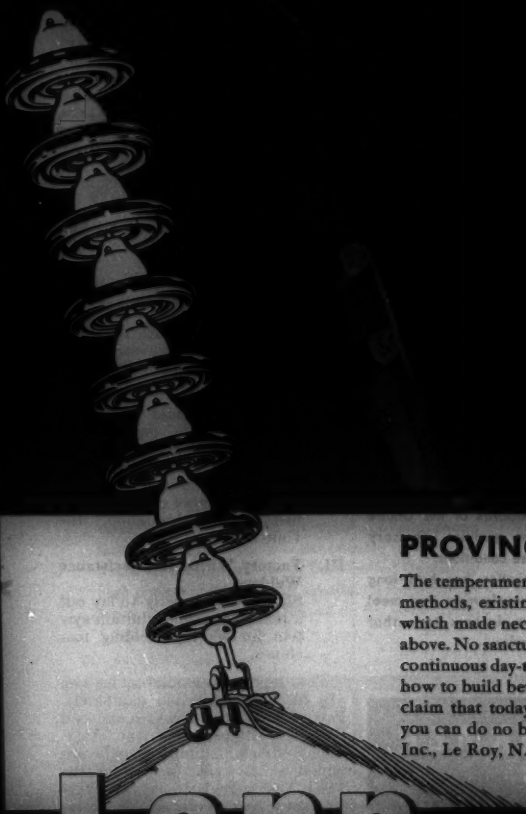

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...Prepared by an AIEE Committee

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I. **Guide to Good Electrical Performance of Resistance-Welding Machines.**
Intended to assist in the preparation of specifications for the purchase of welding machines for the best electrical design, and covers spot, projection, butt, flash, seam, and portable welders.

II. **Resistance-Welder Installation.**
Covers recommended methods of installing resistance-welding equipment, based upon a survey of a number of commercial installations throughout the United States.

III. **Factory Wiring for Resistance Welders.**
Shows how properly to lay out a plant power-distribution system for serving welding machines.

The report is available in two 8½ by 11-inch printed pamphlets, Parts I and II (16 pages) in one, and Part III (12 pages) in the other. Copies of each pamphlet may be obtained at *25 cents each* from the AIEE Order Department, 33 West 39th St., New York, N. Y., payment to accompany order.

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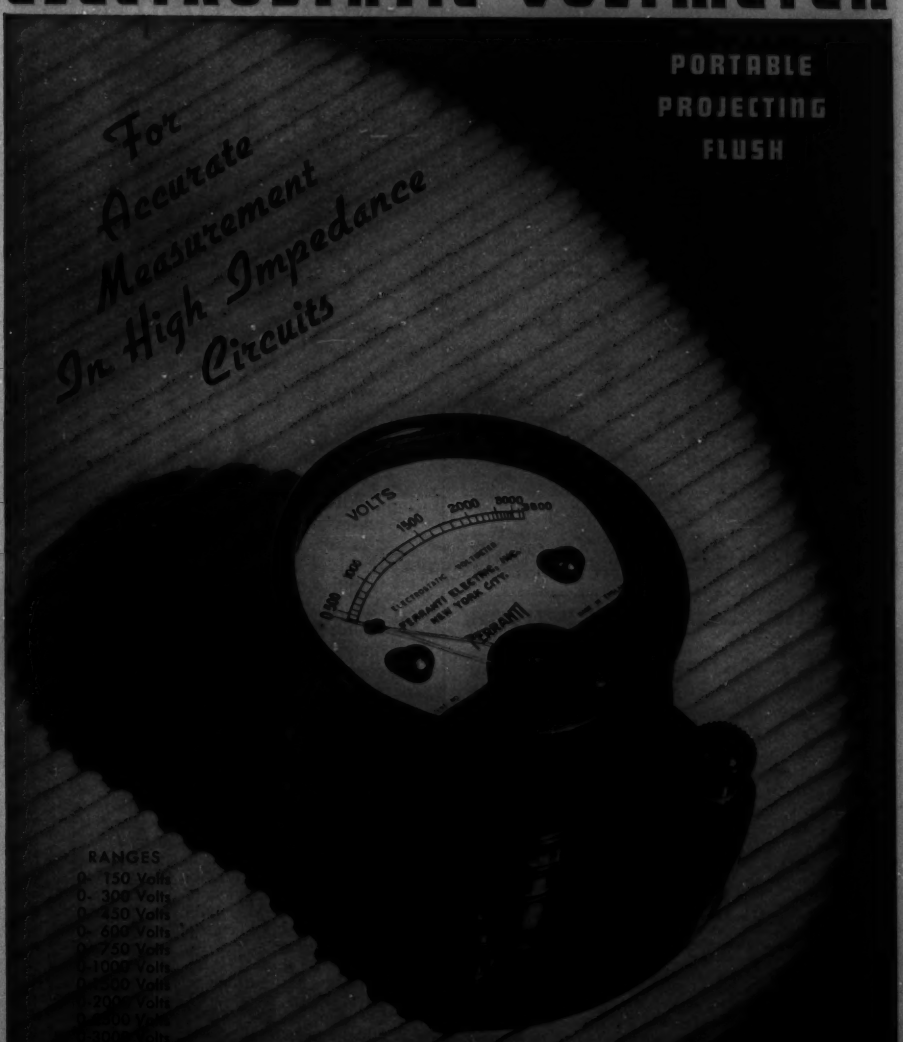

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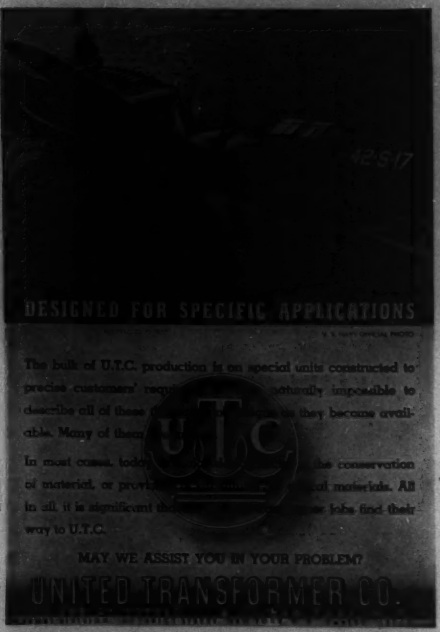

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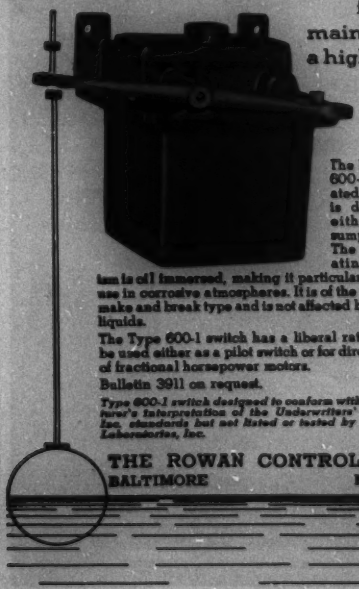

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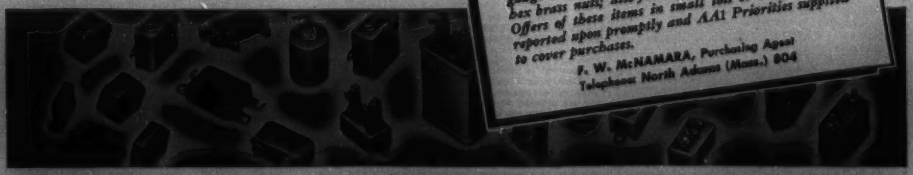

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DESIGNER. Prefer electrical engineering graduate to design power transformers up to 100 K.V.A. and other radio power equipment. Salary, $5000–$6000 a year. Permanent. Location, New Jersey. W-1602.

TRANSFORMER DESIGNER AND ENGINEER with electrical and mechanical experience. Possibly two separate men, one electrical engineer and one mechanical engineer. Location, New York State. W-1631.

ENGINEER with an electrical engineering background and a knowledge and interest in electronics. Work will be more of a commercial or application nature. Should be draft deferred. Salary dependent upon qualifications. Location, Pennsylvania. W-1632.

CIVILIAN INSTRUCTORS, men and women, in radio, for an army technical school. Applicants should have a high school education and at least one of the following: 1. Have recently held an amateur or commercial radio operator's license. 2. One year's experience as a radio engineer, operator or repairman. 3. Successful completion of a six months resident course in radio. 4. One year of college work. Salaries, $1620–$2600 a year. Location, Middlewest. W-1663.

ELECTRICAL ENGINEER OR PHYSICIST who has had considerable experience in the field of electronics or X-ray development or theory. Permanent. Salary, $5200 a year. Location, New York, N. Y. W-1669.

ELECTRICAL ENGINEER, preferably graduate, capable of making circuit analysis, advising on emergency connections, changes in design and operation of power plant and power distribution system in an ammonia and ammonium nitrate plant. Should, preferably, have operating and maintenance experience, as well as a sound engineering and technical background. Location, Arkansas. W-1678C.

PHYSICISTS OR ELECTRICAL ENGINEERS for research and investigation in the electronics field. Instrumentation work in the field. Salary open. Location, Maryland. W-1704.

INSTRUCTORS in Electrical Engineering. Prefer men with some knowledge of radio work. Salary, $4000–$6000 a year. Location, Southwest. W-1723C.

LABORATORY ASSISTANT, young, who has had electrical engineering training. Need not be a graduate, but must have a thorough understanding of resistance breakdown tests and be able to take meter readings and make simple electrical calculations. Man who has some knowledge of radio preferred. Salary open. Permanent. Location, New Jersey. W-1728.

ELECTRICAL ENGINEER to work in contract sales division of a large electrical machinery manufacturing company. Should have some previous sales experience with an electrical background. Salary, $3400–$3000 a year. Location, northern New Jersey. W-1733.

ELECTRICAL-MECHANICAL ENGINEER, with sound engineering background and capable of development to a position of chief engineer. Company makes products in special designed electric furnaces. Salary open. Permanent. Location, Ohio. W-1773.

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ELEC ENGR; 45, married; citizen; B.S. in E.E. and M.E.; registered elec and mech engr; 23 yrs util exper-engg, estimating, des, constrn, oprn and maintenance of distr and transm lines and sub-stations. Desires permanent pos with util in southeastern states. E-73.

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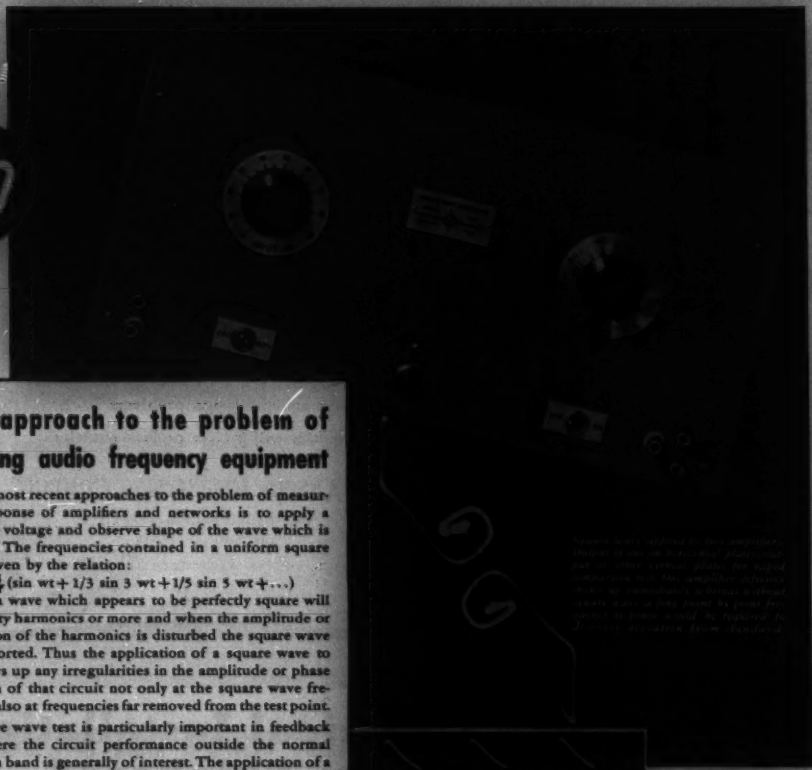
B.S. in E.E.; N.Y. Prof Engr License; married; 17 yrs research, devpmt, methods and control—includes metering, electronics, central and sub-station equipment. Instructor, Executive; permanent pos only. E-75.

ELEC ENGR, 20 yrs util exper, 14 yrs in Brazil with engg registration and legal residence there. Would like to make contact with American organization requiring technical representative in that country. E-76.

ELEC ENGR; Prof License N. Y.; middle-aged, married; executive with exceptional all-around exper, now in charge of design of large plant elec systems, seeks change. E-77.



A new approach to the problem of measuring audio frequency equipment

One of the most recent approaches to the problem of measuring the response of amplifiers and networks is to apply a square wave voltage and observe shape of the wave which is transmitted. The frequencies contained in a uniform square wave are given by the relation:

$$f(t) = \frac{4}{\pi}(\sin wt + 1/3 \sin 3\ wt + 1/5 \sin 5\ wt + \ldots)$$

In practice a wave which appears to be perfectly square will contain thirty harmonics or more and when the amplitude or phase relation of the harmonics is disturbed the square wave will be distorted. Thus the application of a square wave to circuit shows up any irregularities in the amplitude or phase transmission of that circuit not only at the square wave frequency but also at frequencies far removed from the test point.

The square wave test is particularly important in feedback circuits where the circuit performance outside the normal transmission band is generally of interest. The application of a square wave test to a feedback amplifier will show in a single observation whether the amplifier is close to oscillation point.

Square wave distortion from poor response at both low and high frequency. (Oscillogram taken on a typical public address amplifier.)

SPEED UP PRODUCTION AND DEVELOPMENT WORK . . . .

This Square Wave Generator will help you in Production and development work on A. F. amplifiers. As a general purpose instrument for laboratory work and as a time saver in production testing a square wave generator is an important instrument.

The -hp- model 210 Square Wave Generator provides an excellent square wave and is more useful than other instruments of this type because the frequency can be accurately set for quantitative measurements of decrement factor, time and other quantities to transient analysis. It will save valuable time in production testing because one or two observations will check the frequency response of apparatus where heretofore a large number of observations were necessary. This new instrument is an important tool for development work because it will show up phase shift and transient effects, both of which are rather difficult to study by other methods. In one observation a square wave applied to amplifier will check a wide frequency range, a range of 100 to 1 or even more. This is extremely important because once the proper criterion has been established a production test can be set up with one or at the most two observations with a square wave.

No priority needed to avail yourself of our engineering help but -hp- instruments are going all-out for war and quick deliveries can be made only to people engaged in the war effort. However, we are making prompt deliveries to war plants and our capacity for fast production is ample. Write today for information.

Square wave test on feedback amplifier showing amplification peak at 9 times square wave frequency. (A normal frequency response measurement shows flat response from 20 cps to 20 kc.)

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RECOMMENDED PRACTISE FOR

Electrical Installations on Shipboard

(MARINE RULES)

Sec. No. 45
AIEE Standards
With Addenda as
of February 1942

THE latest edition of "Recommended Practise for Electrical Installations on Shipboard" (Marine Rules) is published as Section 45 of the AIEE Standards. The pamphlet contains 100 pages; price is $1.50 (50% discount to members of the AIEE).

These rules have been drawn up to serve as a guide for the equipment of merchant ships with electrical apparatus for lighting, signaling, communication, power and propulsion for both alternating and direct current systems. They indicate what is considered good engineering practise with reference to safety of the personnel and of the ship itself, as well as reliability and durability of the electrical apparatus.

American Institute of Electrical Engineers

33 West Thirty-Ninth Street, New York

Doing the same fundamental Job in 1943 but so much more of it!

Most manufacturers engaged in war production are working on products foreign to their normal efforts. But it's a different story here at WESTON. We have exactly the same job to do because our job is *so fundamental;* but there's much more, *so much more of it.* For precise measurement is vital to the efficient functioning of equipment in *all* branches of a highly mechanized war machine. And while measurement fundamentals have not changed, the universal preference for instruments the way WESTON builds them *has not changed either.*

So WESTON'S job, as we enter the New Year, still remains the job of striving to keep abreast of the country's unprecedented and critical instrument needs. Production has been increased many fold through expanded and scattered manufacturing facilities. And the curve *continues* upward. But never to the point where we must relinquish, *one bit,* our quality standards—'else some pilot's safety might be *less* secure . . . a ship's reckoning *less* accurate . . . a critical power plant *less* efficient.

But achieve the production goal *we will;* without jeopardizing quality . . . without interrupting our continuing development program now focused on instruments to help speed victory. And in accomplishing this goal, we will have equipped ourselves to serve *even better* the new and increased instrument needs of the future . . . the needs of American industry at peace. Weston Electrical Instrument Corporation, 664 Frelinghuysen Avenue, Newark, New Jersey.

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Westinghouse E. & M. Co., E. Pittsburgh
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(Continued on page 46)

Telephone wire coming up

Here's a bomber-gunner hurrying to load his 50-calibre gun. . . .

In peace, a lot of that copper would have gone into new telephone lines. Now it's needed for shooting and winning the war.

That's why we can't build new lines right now. That's why we're saying —"Please don't place Long Distance calls to war-busy centers unless it's absolutely necessary."

Thanks for all your help and we hope you will keep remembering.

BELL TELEPHONE SYSTEM

WAR CALLS COME FIRST

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PRODUCTION TRANSFORMERS

You name the specifications and we'll design the transformers to meet the most exacting performance limitations of your application. Whether it be standard or special characteristics, Acme's trained production organization and specialized transformer manufacturing facilities can serve you better.

For Example

Acme compound-filled communication transformers for mobile and air-borne war equipment are tested to successfully withstand all temperature and climatic conditions.

This Welding Transformer is another special design application. For operation on 115 volt, single phase, 60 cycle primary circuit with secondary characteristics of 0.75 volt, 1600 amperes.

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To eliminate extraneous interference caused by power lines entering shielded test rooms, this Acme Isolating Transformer has a completely shielded secondary winding and shielded secondary terminal leads. Secondary provides a relatively constant voltage for testing purposes, unaffected by the use of instruments, soldering irons, lighting or on-and-off switching. Rated at 2 KVA with 50% overload capacity and 1% regulation at 1 KVA.

THE ACME ELECTRIC & MFG. CO.

22 Water St. Cuba, New York

Acme Electric
TRANSFORMERS

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(*Continued from page 44*)

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Kerite Ins. Wire & Cable Co., New York
National Elec. Products Corp., Pittsburgh
Okonite Company, The, Passaic, N. J.
Okonite-Callender Cable Co., Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

BIBLIOGRAPHY ON CIRCUIT-INTERRUPTING DEVICES

THE second of several technical bibliographies currently in preparation by Institute committees, a "Bibliography on Circuit-Interrupting Devices, 1928–1940," sponsored by the AIEE committee on protective devices, has just been published. This list of more than 850 titles covers the period 1928–1940. It includes all important material on the subject of circuit-interruption published in the United States by the Institute and various technical and trade periodicals, and the principal articles published in other countries.

Following the arrangement of the "Bibliography of Relay Literature, 1927–1929," published in July 1941, the reference items in the "Bibliography on Circuit-Interrupting Devices" are divided according to subject, and within each section are numbered consecutively, subdivided by years, and listed alphabetically for each year. The subject headings are: Circuit Breakers (Air, Oil, Water, Rapid Reclosing, Recovery Voltages, General and Miscellaneous), Enclosed Switchgear, Air Switches, Bus Bars, and Fuses and Fuse Protection.

"Bibliography on Circuit-Interrupting Devices, 1928–1940"

Printed pamphlet, 28 pages, 8½ by 11 inches; 40 cents per copy to AIEE members (80 cents to nonmembers). Discount of 20 per cent on quantities of 10 or more copies mailed to one address at one time. Remittances in New York exchange should accompany orders.

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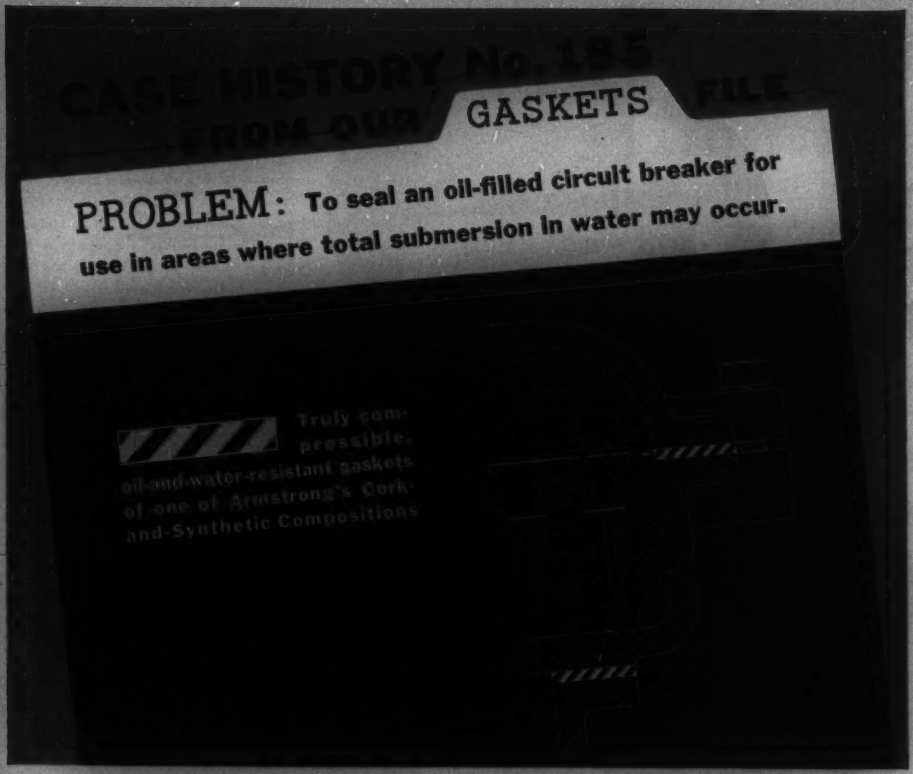
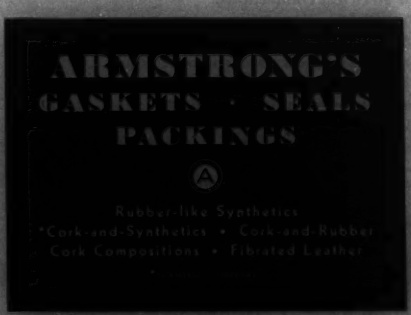

CASE HISTORY No. 185
FROM OUR GASKETS FILE
PROBLEM: To seal an oil-filled circuit breaker for use in areas where total submersion in water may occur.
Truly compressible, oil-and-water-resistant gaskets of one of Armstrong's Cork-and-Synthetic Compositions

A MANUFACTURER of oil-filled circuit breakers had difficulty in securing tightly gasketed joints. Often the equipment was installed below ground level—sometimes near tidewater; thus it was frequently submerged completely. He tried rubber-like synthetic materials which resisted the attack of oil and water. However, since restraining devices could not be used, the gaskets tended to flow or extrude when bolts were drawn down tightly. This resulted in leakage.

Solution

The manufacturer brought his problem to the attention of Armstrong's sealing specialists, who recommended one of Armstrong's Cork-and-Synthetic Compositions (DC-100). Cork makes this composition truly compressible (without flow), and the synthetic does not deteriorate in oil or water. The material was tried in units which were tested under water at five pounds internal air pressure. No leakage occurred. DC-100 was adopted and has given trouble-free service ever since.



Rolls, Sheets, Gaskets, Molded Parts

The solution to *your* problem may likewise be found at Armstrong—where more than fifty efficient sealing materials are available. These include cork, synthetic, cork-and-synthetic, and cork-and-rubber compositions; fiber sheet packings: and rag felts. Armstrong's Compositions are available in large rolls and sheets, in molded shapes, cut gaskets, and extruded rings. Write today for your free copy of the booklet describing these materials. Armstrong Cork Company, Industrial Division, 4002 Arch Street, Lancaster, Pennsylvania.

One glance inside the case of a Frahm Tachometer shows its striking simplicity. The sole mechanism is a set of accurately tuned steel reeds which pick up the minute vibratory impulses of the machine which the instrument need merely touch, and the R.P.M. is indicated on the scale by a sympathetically vibrating reed. Because *no contact with the rotating element is required,* these instruments solve troublesome problems of indicating speed . . . without belts, gears, flexible shafts or electrical connections.

This principle and the method of indication are unique among speed measuring instruments. The Frahm Resonant-Reed Tachometer is as accurate as it is simple, with no parts to wear, adjust, lubricate or renew. It can be used in any position and will give years of trouble-free service. Built in types for permanent mounting . . . and for hand use in servicing, installation and maintenance work. Various ranges available from 900 to 30,000 R.P.M.

For a complete description of Frahm Tachometers together with lists of types and ranges commonly supplied, write for Bulletin 1590EE.

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For manufacturing plants planning an increase or an improvement in power facilities there are many advantages in favor of installing Kuhlman SAF-T-KUHL Transformers.

Because Kuhlman SAF-T-KUHLS are cooled with an inert fluid which is non-inflammable and non-explosive they require no expensive vaults. Thus, they may be installed satisfactorily on beams up near the ceiling thereby saving valuable floor space.

It is often advantageous to divide existing electrical circuits into several sections and install a SAF-T-KUHL Transformer at the load center of each section. The result is a reduction in power losses, better voltage regulation and a considerable saving in the running of long lines of secondary copper.

Write today for further facts about the economical and 100% safe Kuhlman SAF-T-KUHL Transformers.

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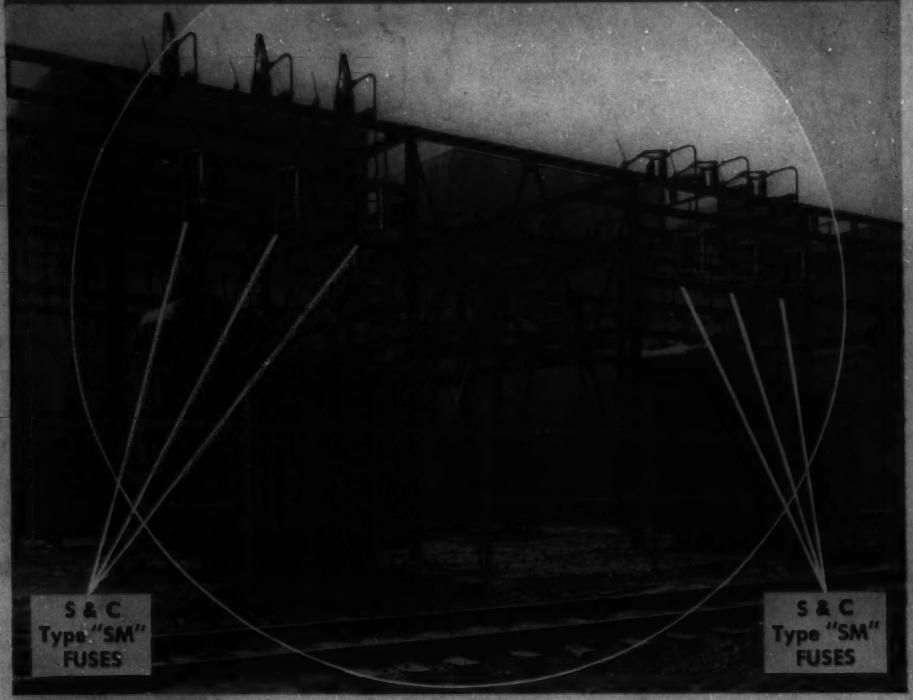

THE vital importance of military equipment production has emphasized the need for unusual care in the selection of power-supply protection because unnecessary interruptions mean serious production delays.

Present engineering practice has dictated the use of dependable S & C Type "SM" Fuses for many important installations. The photograph taken on the property of an aviation motor plant illustrates the small space they require while providing adequate protection. These Fuses are well known for their accuracy, high interrupting capacity, and reliability. They save space, installation time and labor, and their use results in great savings in critical metals. Early deliveries can be made.

Type "SM" Fuse ratings are from 1 to 400 amperes, with short circuit interrupting ratings up to 1,000,000 KVA. They are made for indoor or outdoor service for use on 2300/4000, 6600, 13,200, 22,000 and 33,000 volt circuits.

(Type SMG Fuses are available for 46KV to 138KV circuits)

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SHORT CIRCUIT-INTERRUPTING RATINGS IN R.M.S. AMPERES

Fuse Voltage Rating →		7,500	7,500	15,000	22,000	34,500
Circuit Voltage →		2,300/4,000	6,600	13,200	22,000	33,000
Type and Size of Holder	**SMPC-6	17,500	15,000	12,500	10,000	7,500
	SMP-6	27,500	25,000	20,000	15,000	10,000
	**SMPC-5	30,000	25,000	20,000	17,500	15,000
	SMP-5	40,000	35,000	30,000	25,000	20,000

**Equipped with Condenser

TYPE "SM" POWER FUSES